DEVELOPMENT OF A METHODOLOGY TO DETERMINE APPROPRIATE TRAFFIC CONTROL FOR INTERSECTIONS

Final Report

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Prepared By:

Michael Kyte, Associate Professor
Wade Allen, Undergraduate Assistant
Sharon Feeley, Undergraduate Assistant
Leroy Slemmer, Undergraduate Assistant
Travis Hopkins, Undergraduate Assistant

Department of Civil Engineering
University of Idaho
Moscow, Idaho 83843

Prepared For:

Idaho Transportation Department
P.O. Box 7129
Boise, Idaho 83707

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1. INTRODUCTION

The selection of the appropriate control for an intersection is a crucial decision for the traffic engineer. The engineer must consider such factors as cost, safety, and traffic operations. Three documents, among others, are available to assist the traffic engineer in this assessment: the Manual on Uniform Traffic Control Devices (MUTCD) [1], the Institute of Transportation Engineers' Traffic Engineering Handbook (TEH) [2], and the 1985 Highway Capacity Manual (HCM) [3].

> The MUTCD provides a set of warrants to help determine the appropriate conditions for signalization, two-way stop-control, or all-way stop-control.
>
> The TEH provides useful information on intersection control from several different perspectives, including operational aspects of highway capacity, roadway geometric design, traffic signs and markings, traffic signals, and traffic regulations.
>
> The HCM provides methods for determining the level of service for an intersection based on traffic and geometric conditions, and the kind of control to be used. Unfortunately, there is no consistent measure of effectiveness, or MOE, available: delay is used for signalized intersections, and reserve capacity is used for two-way stop-controlled intersections; no MOE is defined for all-way stop-controlled intersections.

Guidance for making the decision on the appropriate kind of intersection control is, however, incomplete. What is needed is a more comprehensive operational approach based on the traffic flow and geometric conditions likely to be found at the intersection in question. The research results presented in this report are at least a partial solution to this need.

In October 1990, the Idaho Transportation Department and the University of Idaho initiated a cooperative research project to develop a methodology that would allow the traffic engineer to select the appropriate and optimal intersection control for a given set of traffic and geometric conditions using an operational measure of effectiveness. Vehicle delay has been selected as the appropriate measure of effectiveness for this study. The use of delay as the MOE is only recently possible with the development of new delay-based evaluations methods for stop-controlled intersections.

Chapter 2 of this report summarizes how warrants and other guidelines are now used to select the appropriate kind of intersection control. Chapter 3 describes the methods available to calculate delay for various kinds of intersection control using several simulation models. Chapters 4 and 5 describe the results of simulation of single-lane and multi-lane approach intersections. The development of a methodology to determine control based on the results of the simulations is given in Chapter 6. A summary of the research is given in Chapter 7.

2. INTERSECTION CONTROL BASED ON WARRANTS AND OTHER GUIDELINES

This chapter summarizes how warrants and other guidelines are used to help the traffic engineer select the appropriate control at an intersection. The first section describes some of the guidelines available from the TEH. The second section describes the methods for determining level of service based on the HCM. The third section discusses the MUTCD warrant approach to determining intersection control.

2.1 ITE Traffic Engineering Handbook

The ITE Traffic Engineering Handbook provides guidance on intersection control from several different persepctives: operational aspects of highway capacity, roadway geometric design, traffic signs and markings, traffic signals, and traffic regulations. Selected information from the TEH is summarized here.

The TEH notes on p. 352 that there are three primary control methods that can be used to assign the right-of-way at an intersection, two-way stop-control, four-way stop-control, and signal control.

> "The most generally used method of assigning the right-of-way at an intersection are the following controls:
>
> "Two-Way Stop. Where one of the streets at the intersection is more heavily traveled, a designated through street, or a state highway, the stop sign is placed against the traffic on the other street or streets. The sign should be placed against the minor flows of traffic in order to delay as few vehicles as possible.
>
> "Four-Way Stop. Four-way stop-control has the great disadvantage of delaying all vehicles entering the intersection, whereas it should never be necessary to delay more than half of these vehicles. However, it does provide for safe and orderly movements at intersections where higher volumes of traffic must be accomodated without benefit of traffic signals.
>
> "Traffic signals are appropriate under certain circumstances, with specific warrants for installation, as discussed in detail in MUTCD."

From the perspective of traffic signs and markings, the TEH notes on p. 267:

"Regulatory and warning signs are installed because of need and in some cases because of warranting conditions.

"Stop sign warrants. A stop sign may be warranted at an intersection where one or more of the following conditions exists: (1) intersection of a less important road with a main road; an example could be the intersection of two subdivision streets, where application of the normal right-of-way rule is not unduly hazardous, (2) intersection of a county road, city street, or township road with a state highway, (3) street entering a through arterial highway or street, (4) unsignalized intersection in a signal area, and (5) unsignalized intersection where a combination of high speed, restricted view, and accident records indicate a need for control by the stop sign.

"Multi-way stop installations can be used as safety measures at some locations. These are especially useful where the volumes on the intersecting roads are approximately equal and the following conditions have been established: (1) where traffic signals are warranted, multiway stop control is an interim measure that can be installed quickly while arrangements are being made for the signal, (2) when an accident problem as indicated by five or more reported accidents in a twelve month period are of a type susceptible to correction by a multiway stop condition and less restrictive controls have not been successful, and (3) minimum traffic volumes, (a) where the total vehicle volume entering the intersection from all approaches averages at least 500 vehicles per hour for any 8 hours of an average day, and (b) where the combined vehicular and pedestrian volume from minor streets must average at least 200 units per hour for the same 8 hours with an average delay to minor stret traffic of at least 30 sec/veh during the maximum hour, but (c) when the 85th percentile approach speed of the minor street traffic exceeds 40 mph, the minimum volume warrants are 70 percent of the above requirement."

The TEH cautions on p. 279 that traffic signals are not always the most appropriate control device.

"Traffic signals that are appropriately justified, properly designed, and effectively operated can be expected to achieve one or more of the following: (1) to effect orderly traffic movement through an appropriate assignment of right-of-way, (2) to provide for the progressive flow of a platoon of traffic along a given route, (3) to interrupt heavy traffic at intervals to allow pedestrians and cross-street traffic to cross or to enter the main street flow, (4) to increase the traffic handling ability of an intersection, or (5) to reduce the frequency of occurence of certain types of accidents.

"Contrary to common belief, traffic signals do not always increase safety and reduce delay. Experience has indicated that, although the installation of signals may result in a decrease in the number (and severity) of right-angle collisions, signals will, in many instances, result in an increase in rear-end collisions. Further, the installation of signals may not only increase overall delay but may also reduce intersection capacity. Consequently, it is of utmost importance that the consideration of a signal installation and the selection of equipment be based on a thorough study of traffic and roadway conditions by an engineer trained and experienced in this field. This engineer should recognize that a signal should be installed only if the net effect expected to occur (balancing benefits vs drawbacks) will improve the overall safety and/or operations of the intersection.

"Determining Need For Traffic Signal Control." MUTCD defines a system for establishing the need for a signal installation at a particular location using a common denominator known as "signal warrants".

"A warrant represents the *lowest* threshold at which traffic signals *could*, not *should*, be installed.

With respect to roadway geometric design, the TEH notes on p. 193:

"Intersections at-grade are unique elements of the highway. By definition, they represent points of potential vehicle conflict and are thus susceptible to accident potential. In urban areas, intersections are of such importance that they control the capacity of a street network.

"Intersection design combines aspects of vehicle operational and driver performance characteristics. A prime consideration in intersection design is the type of traffic control required.

"Two prime objectives of any intersection design are operational quality and safety. Stated differently, the design and traffic control scheme should optimize the operational quality of flow through the intersection; and the intersection should be designed to minimize accidents and their adverse consequences. These stated objectives are more precisely defined as follows: (1) points of conflict should be minimized, (2) conflict areas should be simplified, (3) conflict frequency should be limited, and (4) conflict severity should be minimized."

Further on this topic on p. 197:

"Traffic Control Devices. It is particularly important to consider the effects of and requirements for traffic control devices in the design of intersections. MUTCD specifies desirable controls for locations of signals, signs, and pavement markings. These should clearly be considered as design proceeds. ... One aspect of traffic control is that it can change. An intersection in an urban area may initially be stop-controlled, but eventually converted to signal control as traffic volumes increase. The design should accomodate eventual conversion to signal control without the need for major reconstruction."

While the HCM provides a consistent level of service ranking for evaluating the operational aspects of highway capacity, the TEH notes on p. 145 that the procedures for signalized intersections and two-way stop-controlled intersections

"... were developed from different concepts using different data bases, and no direct correlation has been established between levels of service at traffic signals and at unsignalized locations."

2.2 Highway Capacity Manual

The HCM provides computational methods for evaluating the capacity and level of service for a variety of transportation facilities. Methods producing level of service estimates are provided for signalized intersection (chapter 9) and unsignalized intersections (chapter 10). Unfortunately, while both methods produce levels of service, the measures of effectiveness are not consistent. The MOE is delay for signalized intersections and reserve capacity for unsignalized intersections. Thus while the performance of each kind of control can be evaluated separately, there is no link by which to compare the relative performance of each. This problem has been somewhat ameliorated by the adoption of an interim procedure for AWSC intersections, which produces an estimate of vehicle delay as the measure of effectiveness. [4]

2.3 Manual on Uniform Traffic Control Devices

MUTCD describes the proper use of stop control on pages 2B-2 through 2B-4:

> "Stop signs are intended for use where traffic is required to stop. ... Because the stop sign causes a substantial inconvenience to motorists, it should only be used where warranted. A stop sign may be warranted at an intersection where one or more of the following conditions exist: (1) intersection of a less important road with a main road where application of the normal right-of-way is unduly hazardous, (2) street entering a through highway or street, (3) unsignalized intersection in a signalized area, or (4) other intersections where a combination of high speed, restricted view, and serious accident record indicates a need for control by stop sign."

MUTCD notes on page 2B-3 that "the Multiway Stop installation is useful as a safety measure at some locations. It should ordinarily be used only where the volume of traffic on the intersecting roads is approximately equal. A traffic control signal is more satisfactory for an intersection with a heavy volume of traffic." A multiway stop sign may be warranted if: (1) where traffic signals are warranted and urgently needed, the multiway stop is an interim measure that can be installed quickly to control traffic while arrangements are being made for the signal installation, (2) an accident problem, as indicated by five or more reported accidents of a type susceptible of correction by a multiway stop installation in a 12-month period." MUTCD also establishes minimum vehicular and pedestrian volume warrants.

Eleven signal warrants are identified by MUTCD: (1) minimum vehicular volume, (2) interruption of continuous traffic, (3) minimum pedestrian volume, (4) school crossings, (5) progressive movement, (6) accident experience, (7) systems, (8) combination of warrants, (9) four hour volumes, (10) peak hour delay, and (11) peak hour volume.

3. USING DELAY TO EVALUATE INTERSECTION PERFORMANCE

One of the major criticisms of the use of traffic warrants from MUTCD is that the warrants do not provide a sense of the level of service or quality of the performance likely to result with different kinds of intersection control. While the 1985 HCM provides estimates of level of service for two kinds of intersections, two problems exist. First, the MOE's for signal control and two-way stop-control are not consistent, and second, no MOE is given for all-way stop-controlled intersections.

Fortunately, delay forecasting models have recently been developed for stop-controlled intersections. The Highway Capacity Committee of the Transportation Research Board has now adopted an interim capacity and level of service procedure for AWSC intersections that yields estimates of delay given traffic and geometry conditions. [4] Two other methods are also available to evaluate TWSC intersections. A simulation model, KNOSIMO, was developed by Werner Brilon and Michael Grossman of Ruhr University, Bochum, Germany [5]. Empirically-based capacity and delay equations for TWSC intersections have been developed at the University of Idaho [6].

3.1 Simulation Models and Delay Equations

A number of simulation models are available to study the performance of intersections. Some of these models are listed in Table 1; the delay equations that are included in these models are described in detail below.

Webster's Signal Delay Model. The standard delay equation for fixed-timed signalized intersections was developed by Webster [7]. It is the basis for the TRANSYT 7F model, the PASSER II model, and the HCM/HCS model. Webster's model includes three components, one each for uniform delay (d_u), random delay (d_r), and oversaturated delay (d_s).

Table 1. Intersection Simulation Models

Model	Intersection Control	Description
TRANSYT 7F	Signal	Macroscopic, deterministic
PASSER II	Signal	Macroscopic, deterministic
HCM/HCS	Signal, TWSC	Macroscopic, deterministic
KNOSIMO	TWSC	Macroscopic, stochastic
NETSIM	Signal, AWSC, TWSC	Microscopic, stochastic
TEXAS	Signal, AWSC, TWSC	Microscopic, stochastic
HCM Interim Model	AWSC	Macroscopic, deterministic
Univ of Idaho	TWSC	Macroscopic, deterministic

$$d = d_u + d_r + d_s \tag{1}$$

$$d_u = \frac{C(1-\lambda)^2}{2(1-\lambda X)} \tag{2}$$

where C is the cycle length, λ is the ratio of the green time g to the cycle length C, and X is the degree of saturation, or the volume/capacity ratio.

$$d_r = \frac{X^2}{2q(1-X)} \tag{3}$$

where q is the approach flow in vehicles per second.

$$d_s = 0.65 \left(\frac{C}{q^2}\right)^{1/3} X^{2+5\lambda} \tag{4}$$

The uniform delay component is based on the assumption that vehicles arrive at the intersection in a uniform pattern. This term dominates the other two as long as the volume/capacity ratio is less than about 0.8 or 0.9. The random delay component begins to predominate for high volume/capacity ratios.

According to Webster, the last term, included as an empirical correction term, has a value in the range of 5 to 15 percent of the total delay, in most cases.

TRANSYT 7F Model. The TRANSYT delay model includes Webster's uniform delay term plus a combination of the random and oversaturated delay terms. The uniform delay term is the same as given in equation (2) above. The random and oversaturated terms are combined into one term as follows:

$$d = \left[\left(\frac{B_n}{B_d}\right)^2 + \frac{X^2}{B_d}\right]^{1/2} - \frac{B_n}{B_d} \qquad (5)$$

where

$$B_n = 2(1-X) + Xz \qquad (6)$$

$$B_d = 4z - z^2 \qquad (7)$$

$$z = \left(\frac{2X}{v}\right)\left(\frac{60}{T}\right) \qquad (8)$$

and where v is the volume in vehicles per hour and T is the period length, usually 60 minutes. Figures 1 and 2 show plots of delay as estimated by both the Webster and TRANSYT 7F models.

PASSER II Model. The delay model used by PASSER II is also based on the Webster model.

$$d = \frac{VR(1-g/C)^2}{2V[1+VR/(S-VG)]} + \frac{X^2}{2(V/3600)(1-X)} - .65(C/(v/3600))^{1/3}X^{2+5g/C} \qquad (9)$$

where d is the average vehicle delay on the approach in seconds per vehicle, VR is the average arrival flow rate on the approach during the red phase for the given movement in vehicles per hour, g/C is the ratio of the effective green time on the approach to the cycle length, C is the cycle length, V is the average arrival flow rate on the approach in vehicles per hour, S is the saturation flow rate in vehicles per hour, VG is the average arrival flow rate on the approach during the green phase, and X is the volume/capacity ratio.

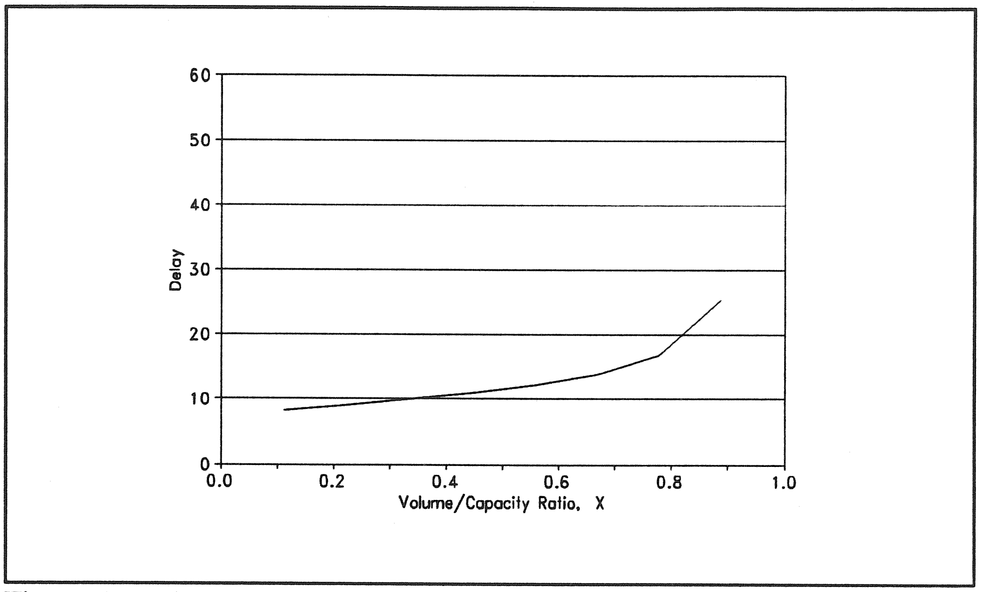

Figure 1. Webster Delay Model

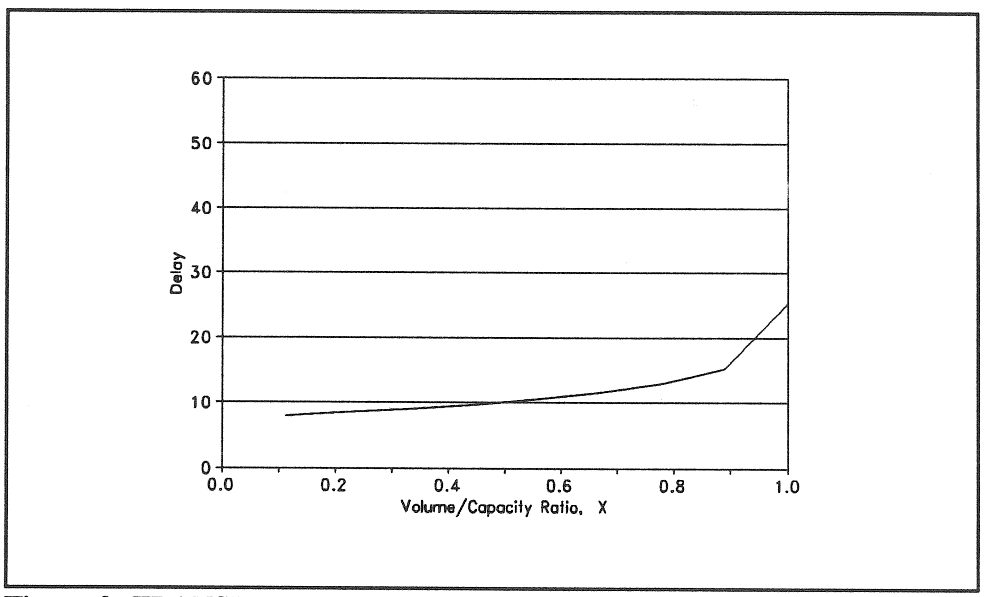

Figure 2. TRANSYT 7F Delay Model

HCM/HCS Signal Model. The HCM delay model includes both uniform and random delay terms.

$$d_u = 0.38C\frac{[1-g/C]^2}{1-(g/C)(X)} \quad (10)$$

$$d_r = 173X^2\left[(X-1) + \sqrt{(X-1)^2 + (16X/c)}\right] \quad (11)$$

University of Idaho TWSC Intersection Model. The capacity and delay equations for TWSC intersections were developed at the University of Idaho [6]:

$$c = 906-0.82q_c, \; if \; q_c \leq 600 \quad (12)$$

$$c = 623-0.28q_c, \; if \; q_c \geq 600 \quad (13)$$

where q_c is the major street flow and c is the capacity of the minor street approach.

$$d = 40.079e^{-0.0035(c-q_s)} \quad (14)$$

where d is total delay, c is capacity of the minor street approach, q_s is the flow on the minor street approach, and q_r is the reserve capacity, or c - q_s.

Interim Model For AWSC Intersections. The capacity and delay equations that are included in the new AWSC procedures are given below.

$$c = 1000\left(\frac{q_s}{q_i}\right)+700\left(\frac{q_o}{q_i}\right) \quad (15)$$

where q_s is the subject approach flow, q_o is the opposing approach flow, q_i is the total intersection flow, and c is the capacity of the subject approach flow.

$$d = e^{3.8X} \quad (16)$$

where d is the subject approach delay and X is the degree of saturation, q_s/c.

3.2 Using Delay Forecasts

When using delay as a basis for comparing intersection performance, one must be careful in the way in which this parameter is applied. Both average delay for the entire intersection as well as the delay experienced on each approach must be considered together.

This can be illustrated when considering the nature of operation of each of the three kinds of intersection control. At a signalized intersection, the cycle time is allocated among the competing approaches, and the length of the cycle itself has a great effect on delay. At TWSC intersections, vehicles on one set of approaches experience little or no delay, while vehicles on the other approaches are delayed based on the traffic flow rates on the major street. All vehicles are delayed, at least a minimal amount, at AWSC intersections. The level of delay is a function of the flow rates on the various approaches.

3.3 Selection of Simulation Models

A thorough assessment of the simulation models listed in Table 1 was undertaken. The purpose of this assessment was to identify those models that would provide the most accurate forecasts of delay based on traffic and geometric conditions for signal, all-way stop, and two-way stop control.

The TRANSYT 7F model was selected as the simulation model for signalized intersections. TRANSYT 7F has a realistic traffic flow model and can provide optimized cycle length and green splits for a given set of traffic conditions. It is also one of the most widely used simulation models for signalized intersection in the U.S. PASSER II is also a widely used model but is intended more for arterial segments with progressive signal systems than for isolated signalized intersections. NETSIM and TEXAS are both microscopic simulation models and offer more complexity than was needed for this study. The HCS does not provide for optimization of signal timings, one of the requirements for this study.

The new interim procedure for AWSC intersections was selected for use in this study since it is the only delay-based model available for AWSC intersections.

The University of Idaho simulation model for TWSC intersections was selected since it is the only delay-based model available that was developed for U.S. traffic conditions. The KNOSIMO model is an excellent simulation model and does provide delay estimates. While it has been calibrated for German conditions, it has not been widely tested as yet in the U.S. The NETSIM and TEXAS models are microscopic simulation models; both yield delay forecasts for TWSC intersections. Neither, however, has been validated with field data from TWSC intersections. Finally, the HCS model does not produce delay estimates for TWSC intersections.

4. SIMULATION OF SINGLE LANE APPROACH INTERSECTIONS

In this chapter, the results of the simulation runs for single-lane approach geometry will be discussed. The simulation methodology is described in the first section. The simulation results are presented in the second section. Comparisons of subject approach delay and intersection delay estimates are given in the third and fourth sections. Determination of optimal control for different flow rate ranges based on both subject approach delay and intersection approach delay are presented in the fifth and sixth sections of this chapter.

4.1 Methodology

To compare the performance of an intersection with different kinds of control, simulation runs were made for a range of traffic flow conditions. Flow rates were varied from 100 vph to 1000 vph on each of the four intersection approaches. Turning movements were assumed to be zero.

Three simulation procedures were used. For signalized intersections, signal timings were computed and optimzed and delay was estimated using TRANSYT 7F. Capacity and delay equations developed at the University of Idaho were used to compute delay for TWSC intersections. Capacity and delay equations from the new interim procedures were used to compute delay for AWSC intersections.

One issue that must be considered in this comparison is the signal timing strategy. One strategy is to assume a fixed-time 60 second cycle with an equal distribution of green time, a standard timing plan for many intersections. Another strategy is to optimize the cycle length and green splits based on traffic flows on the various intersection approaches. The latter approach was adopted here since in order to provide a fair comparison with the stop-controlled intersections, it was felt that the traffic engineer would likely determine an optimal signal cycle and green split for a signalized intersection. These optimal timing parameters are used in the simulations that are subsequently described in this report.

4.2 Simulation Results

The results of the intersection simulations are given in Tables 2 through 21 in the Appendix. The first set of tables (2 through 11) gives delay estimates for the subject approach. The second set of tables (12 through 21) gives the overall delay estimates for the intersection. Note that when delay estimates exceeded 90 seconds per vehicle, no further simulations were run for that set of traffic flow rates.

A further point should be made regarding the terms used to describe traffic volumes or flow rates in this report. When the four individual intersection approaches are described, they are referred to with respect to one of the approaches, the subject approach. The other three approaches are described as the opposing approach and the conflicting (from the left and from the right) approaches. See Figure 3. The approaches are also referred to as the minor street (the combined volumes on the subject and opposing approaches) and the major street (the combined volumes on the conflicting approaches). See Figure 4.

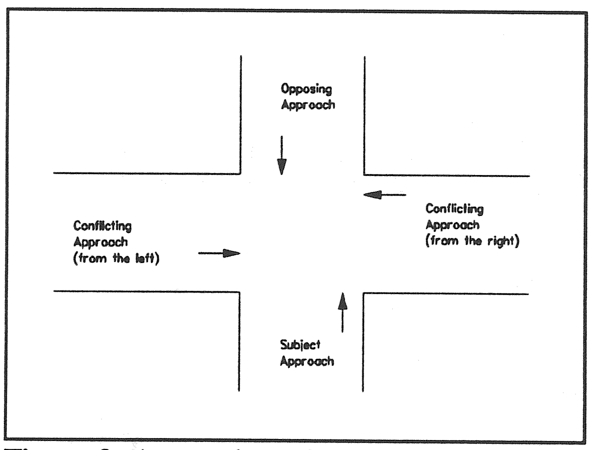

Figure 3. Approach Designations

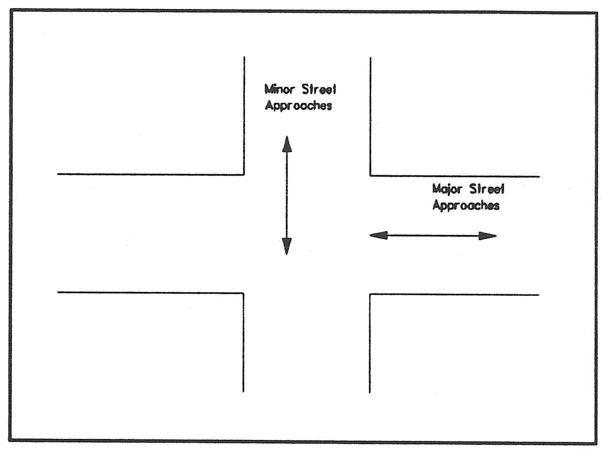

Figure 4. Approach Designations

Subject Approach Delay. Figures 5 through 10 show two-dimensional contour plots and three dimensional surface plots of subject approach delay as a function of the traffic flows on the major street (sum of conflicting approach volumes) and the minor street approaches (sum of the subject and opposing approach volumes). In general, all of the plots show that delay increases exponentially, though at different rates, as flow rates increase. Subject approach delay at *signalized intersections* is less sensitive to the major street flow since all approaches are periodically assigned to the right-of-way or green time. At low minor street volumes, the subject approach receives only minimal green time, thus long delays result. As minor street volumes increase, more green time is allocated to the subject approach and delay decrease. At high minor street volumes, as the intersection nears capacity, delay increases. For *AWSC intersections,* minor street delay steadily increases when either the major or mnor street volumes increase.

Delay at *TWSC intersections* is most sensitive to major street flow since the minor street approach is dependent on suitable gaps to enter the traffic stream. As major street volumes increase, acceptable gaps are fewer so delay increases. As minor street volumes increase, longer queues develop at the stop line, so delay also increases.

Intersection Delay. Figures 11 through 16 show two-dimensional and three dimensional contour plots of intersection delay as a function of the traffic flows on the major and minor street approaches. Since major street traffic is not delayed at TWSC intersections, intersection delay is primarily a function of minor street volume. Intersection delay at AWSC intersection increases uniformly as flow on both the major and minor street approaches increases.

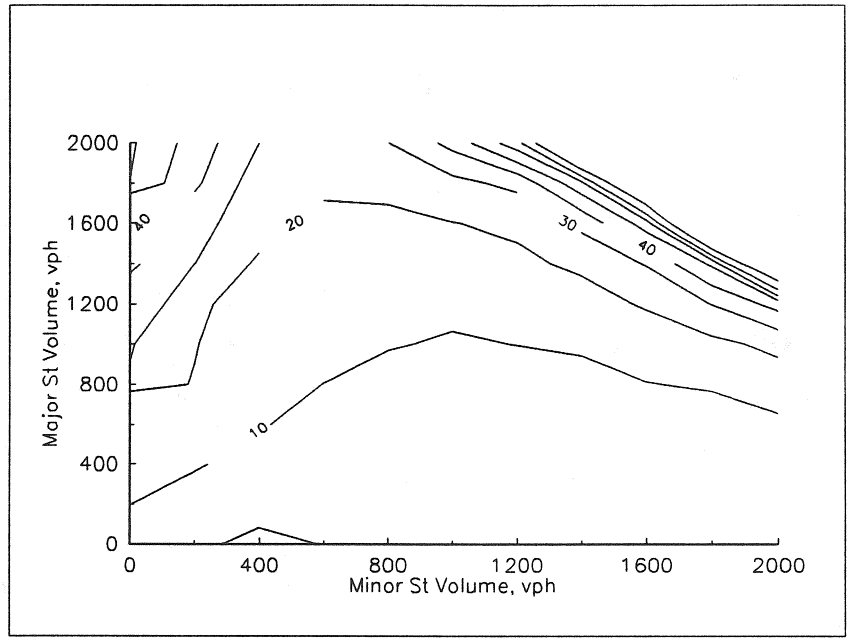

Figure 5. Subject Approach Delay, Signalized Intersection

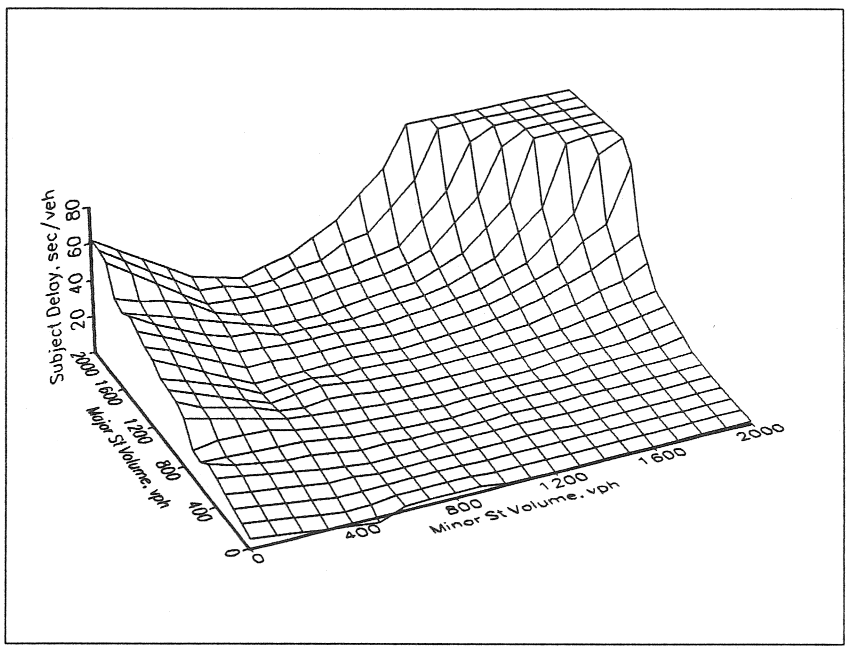

Figure 6. Subject Approach Delay, Signalized Intersection

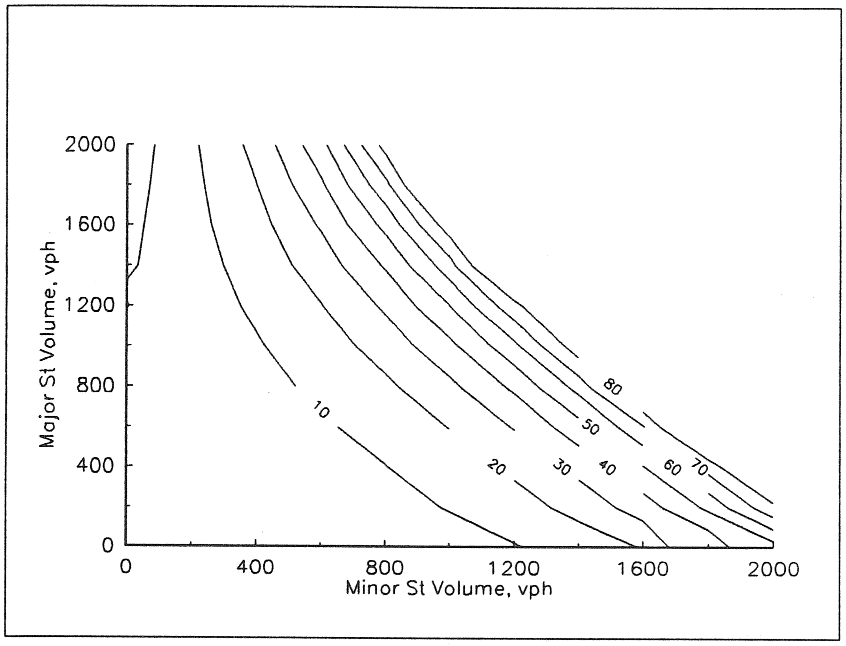

Figure 7. Subject Approach Delay, AWSC Intersection

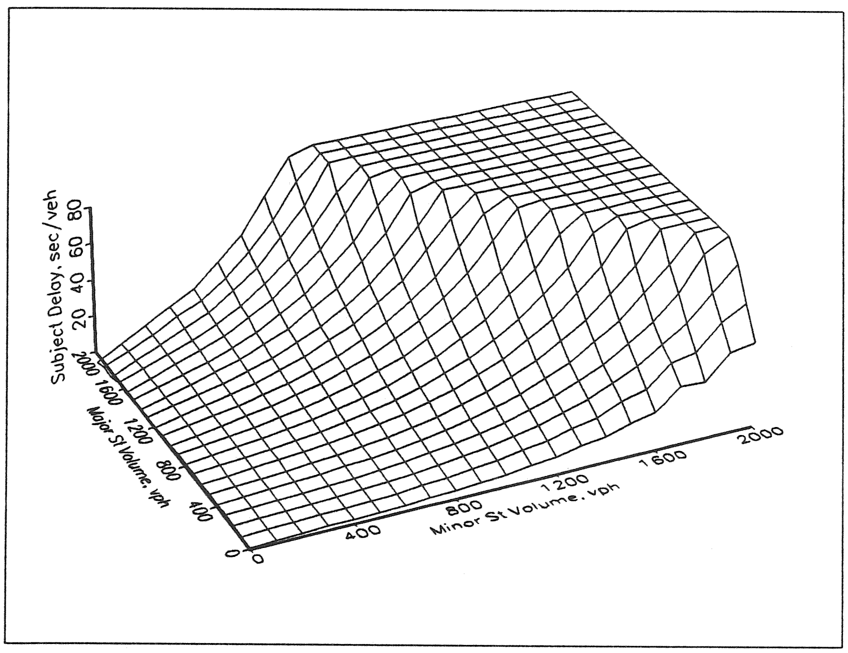

Figure 8. Subject Approach Delay, AWSC Intersection

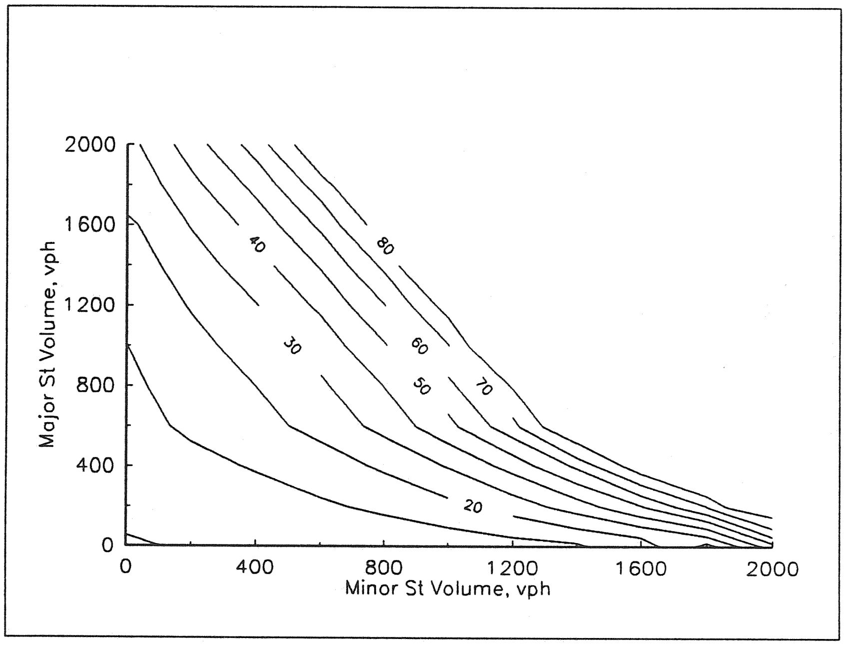

Figure 9. Subject Approach Delay, TWSC Intersection

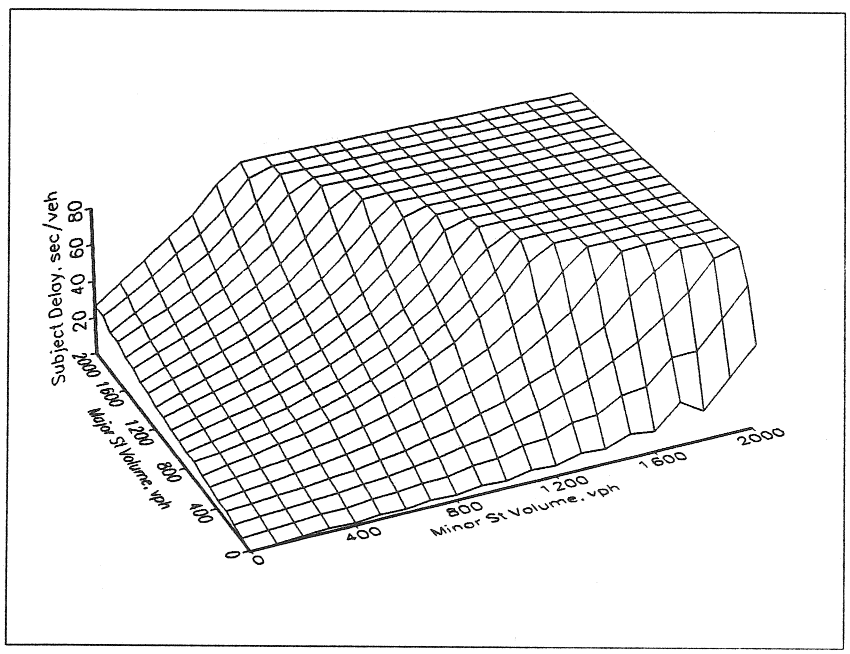

Figure 10. Subject Approach Delay, TWSC Intersection

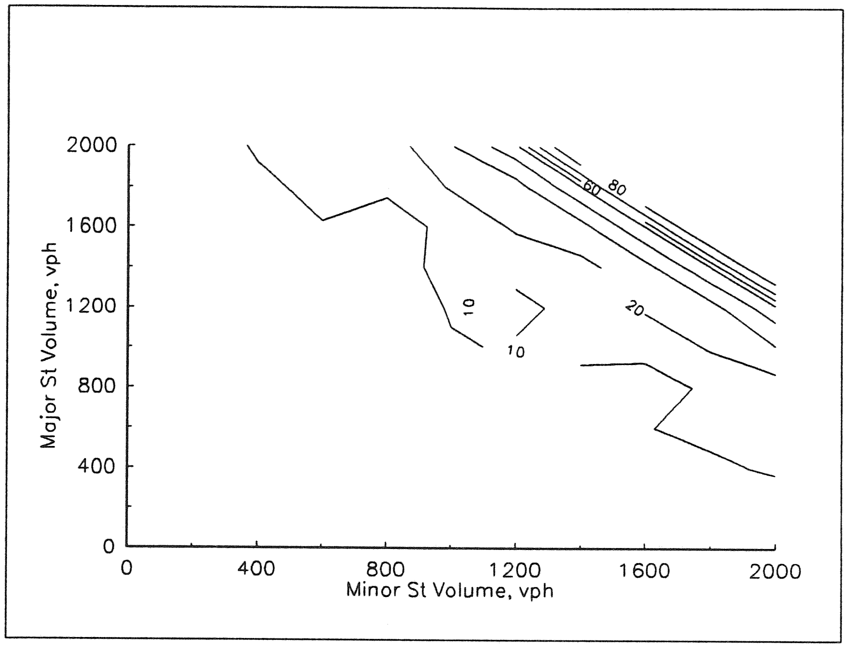

Figure 11. Intersection Delay, Signalized Intersection

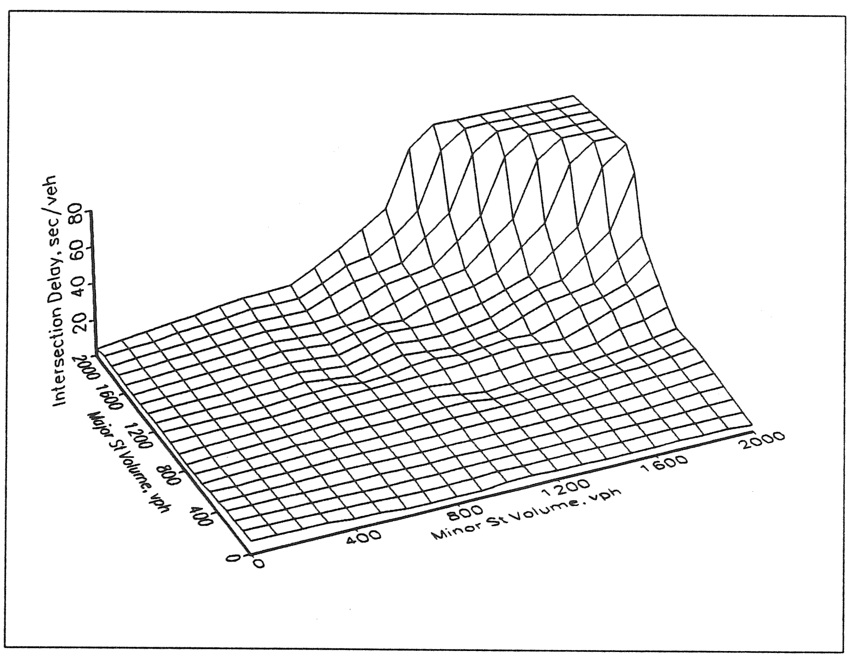

Figure 12. Intersection Delay, Signalized Intersection

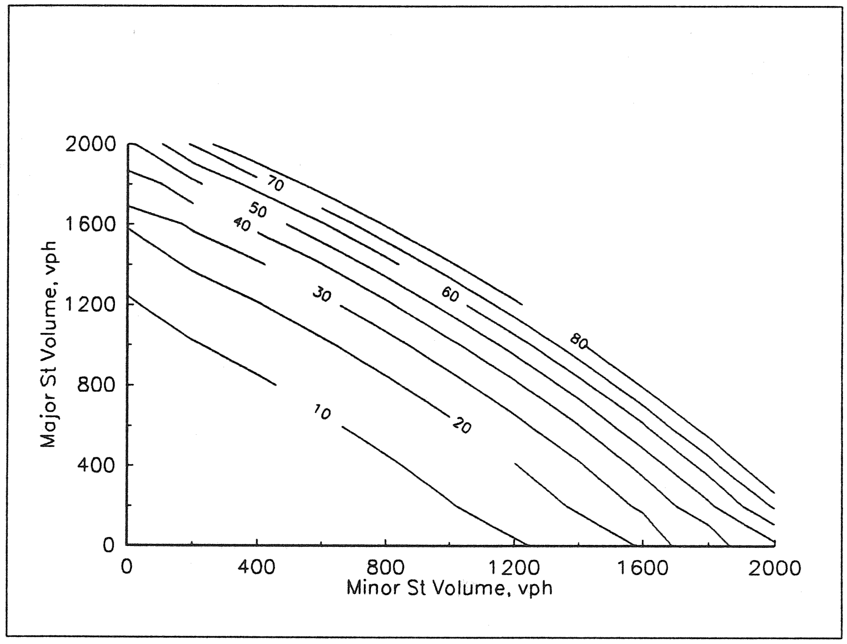

Figure 13. Intersection Delay, AWSC Intersection

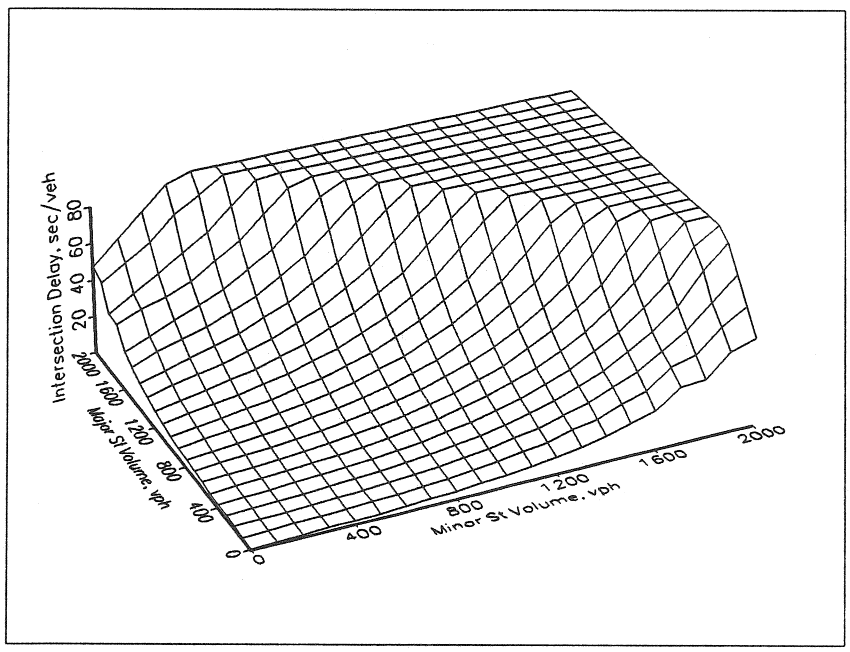

Figure 14. Intersection Delay, AWSC Intersection

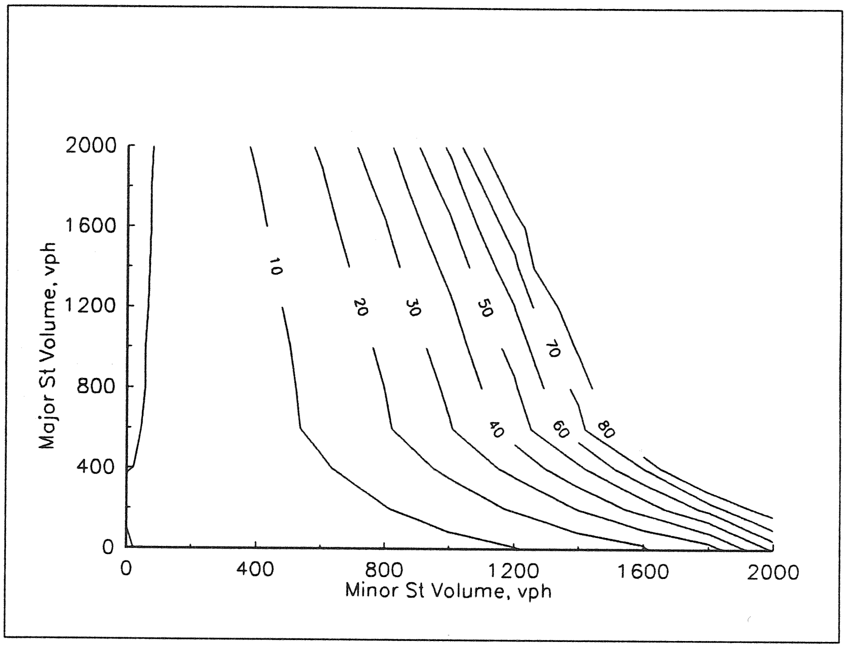

Figure 15. Intersection Delay, TWSC Intersection

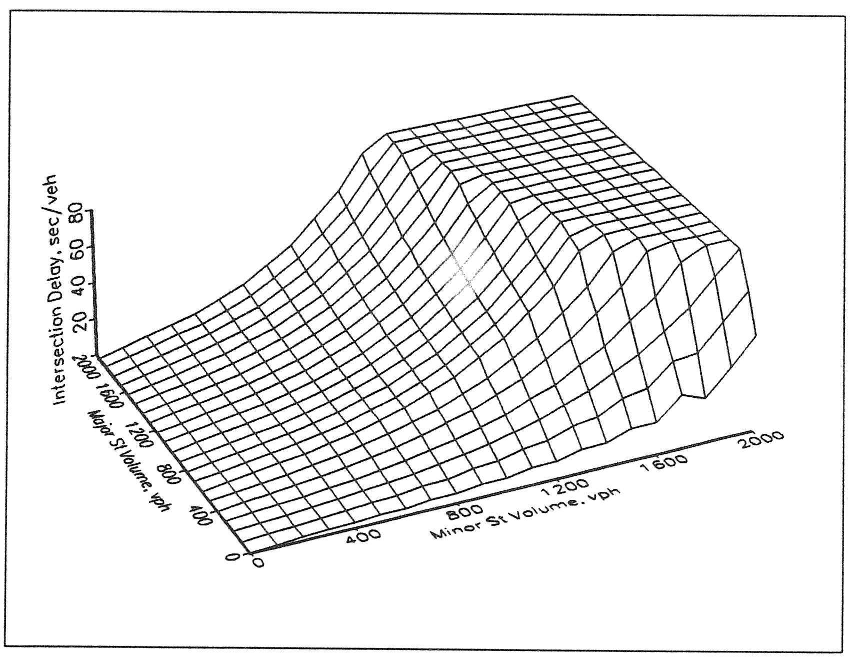

Figure 16. Intersection Delay, TWSC Intersection

4.3 Comparison of Subject Approach Delay Estimates

Average delays per vehicle on the subject approach estimated by the simulation models were plotted to compare the performance of the three control types. The graphs on the next several pages are plots of average vehicle delay on the subject approach vs subject approach volume, for ten different levels of conflicting flow rates. Examination of these ten graphs show that, as expected, signal control yields minimum delay values for the broadest range of traffic flow rates. The following specific trends can be noted:

1. When subject approach flow rates are less than 200 to 300 vph, even at higher conflicting approach flow rates, AWSC yields the minimum delay.

2. When subject approach flow rates exceed 200 to 300 vph, signal control yields the minimum delay.

3. TWSC never provides for lower delay than either signalized intersections or AWSC intersections.

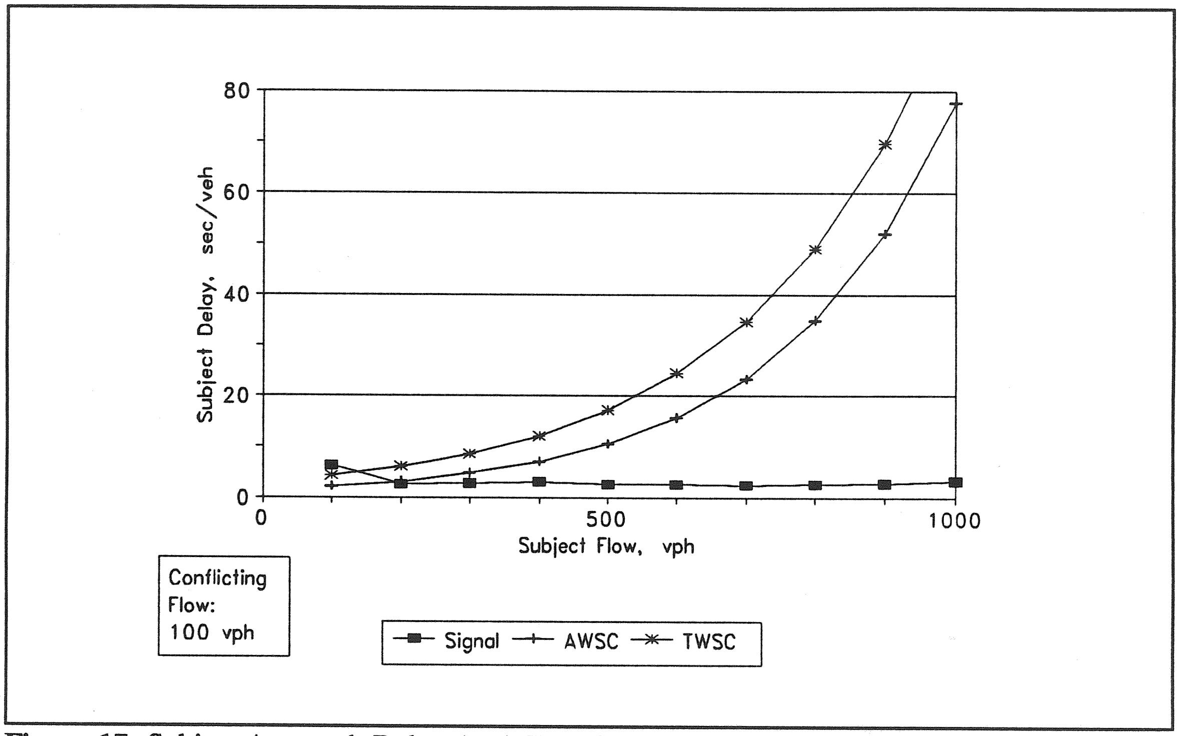

Figure 17. Subject Approach Delay As A Function of Subject Approach Flow

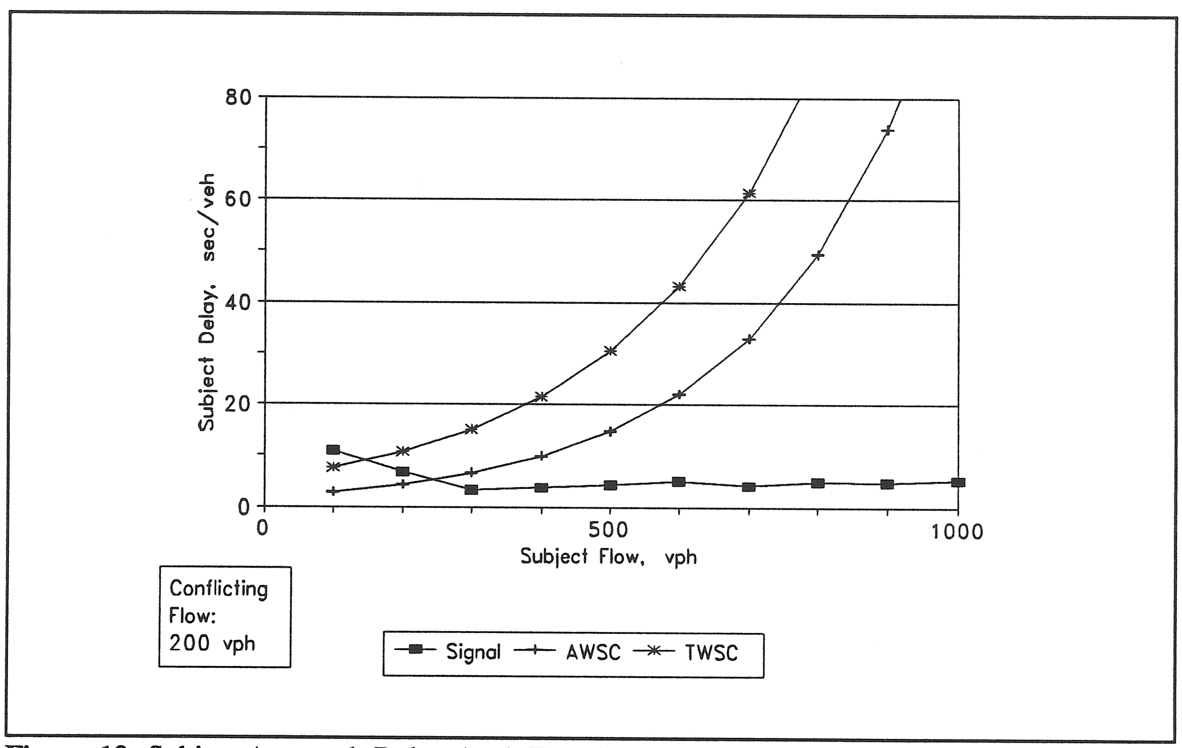

Figure 18. Subject Approach Delay As A Function of Subject Approach Flow

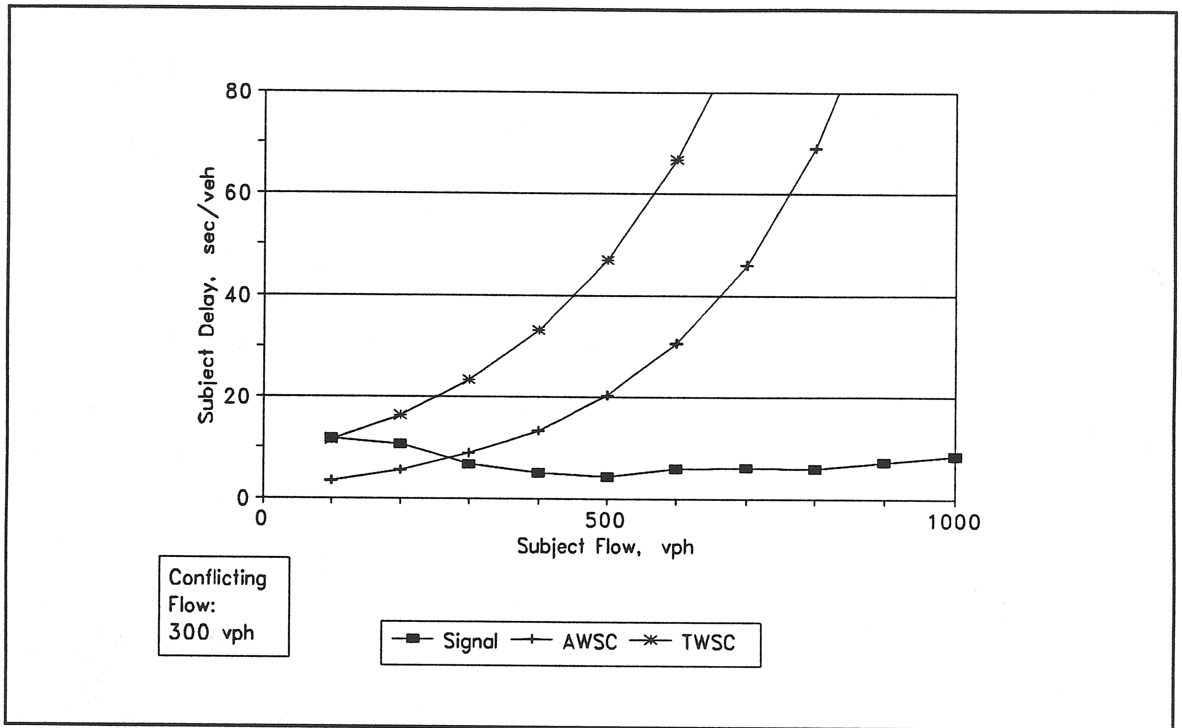

Figure 19. Subject Approach Delay As A Function of Subject Approach Flow

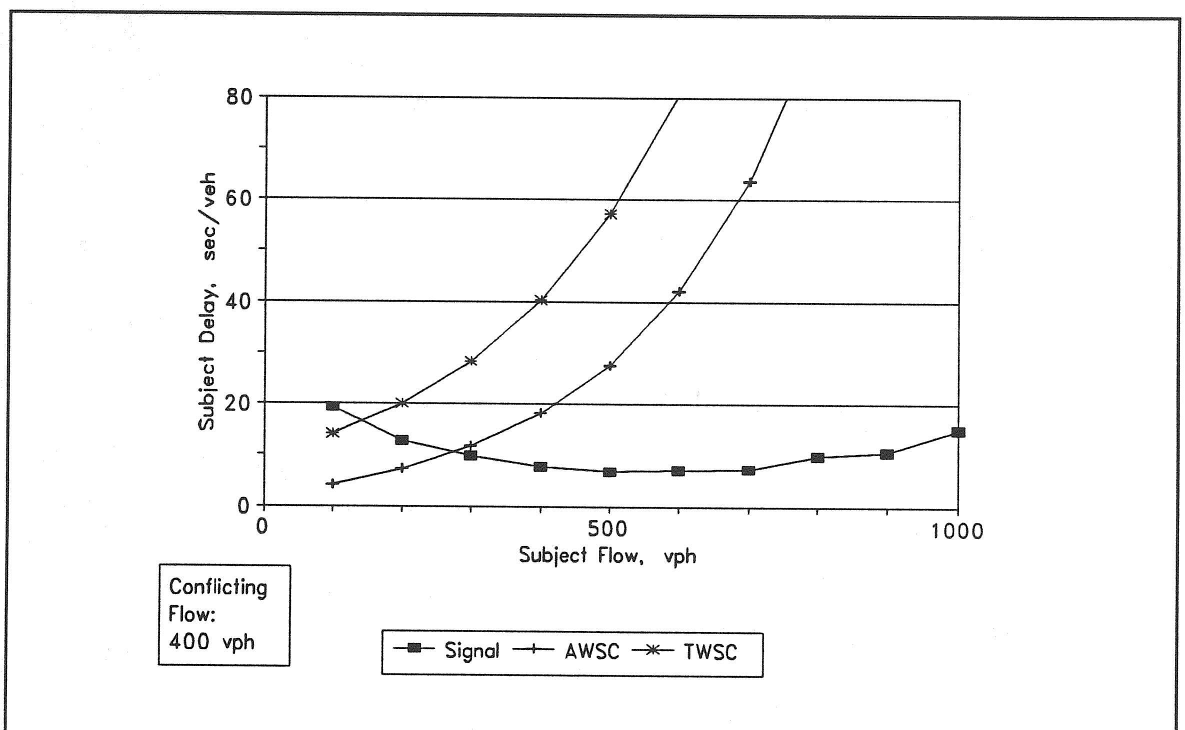

Figure 20. Subject Approach Delay As A Function of Subject Approach Flow

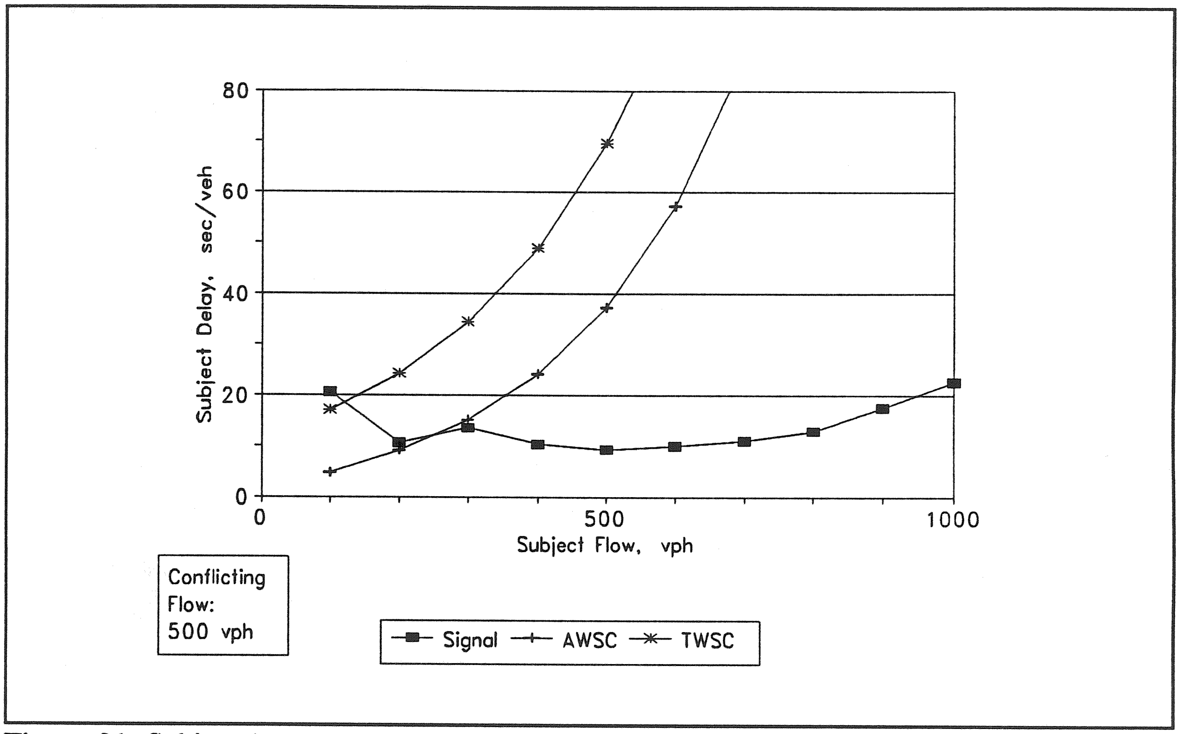

Figure 21. Subject Approach Delay As A Function of Subject Approach Flow

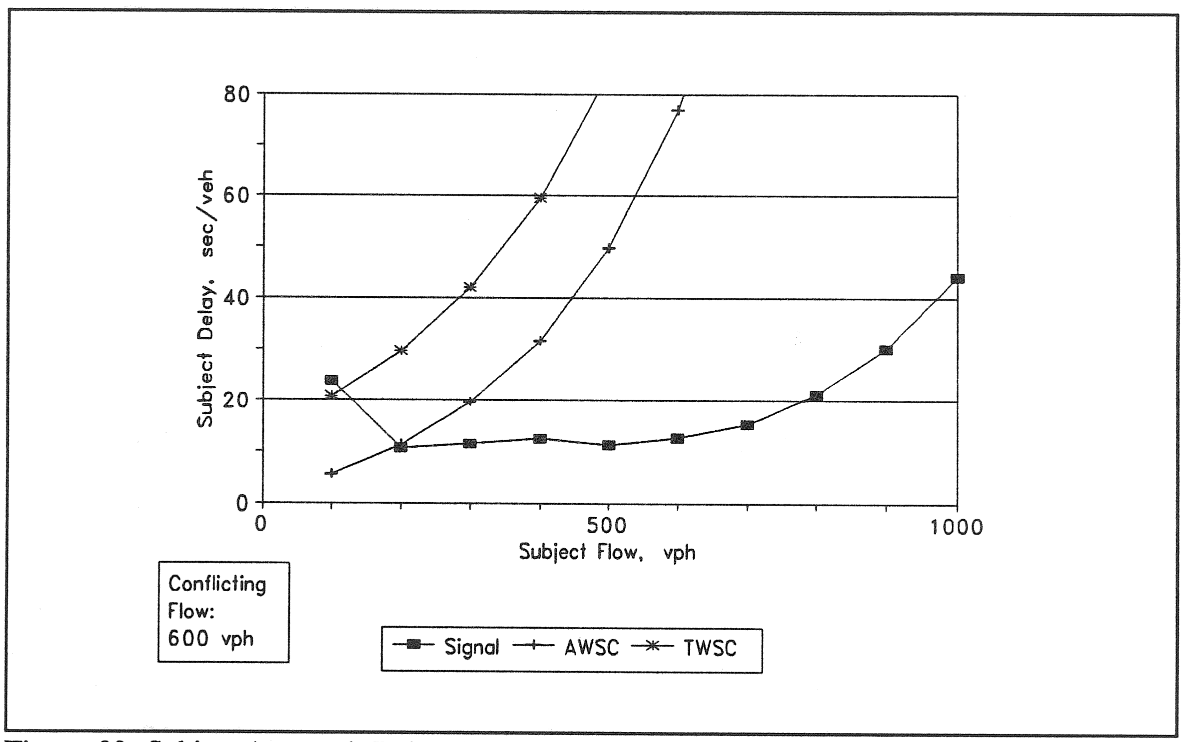

Figure 22. Subject Approach Delay As A Function of Subject Approach Flow

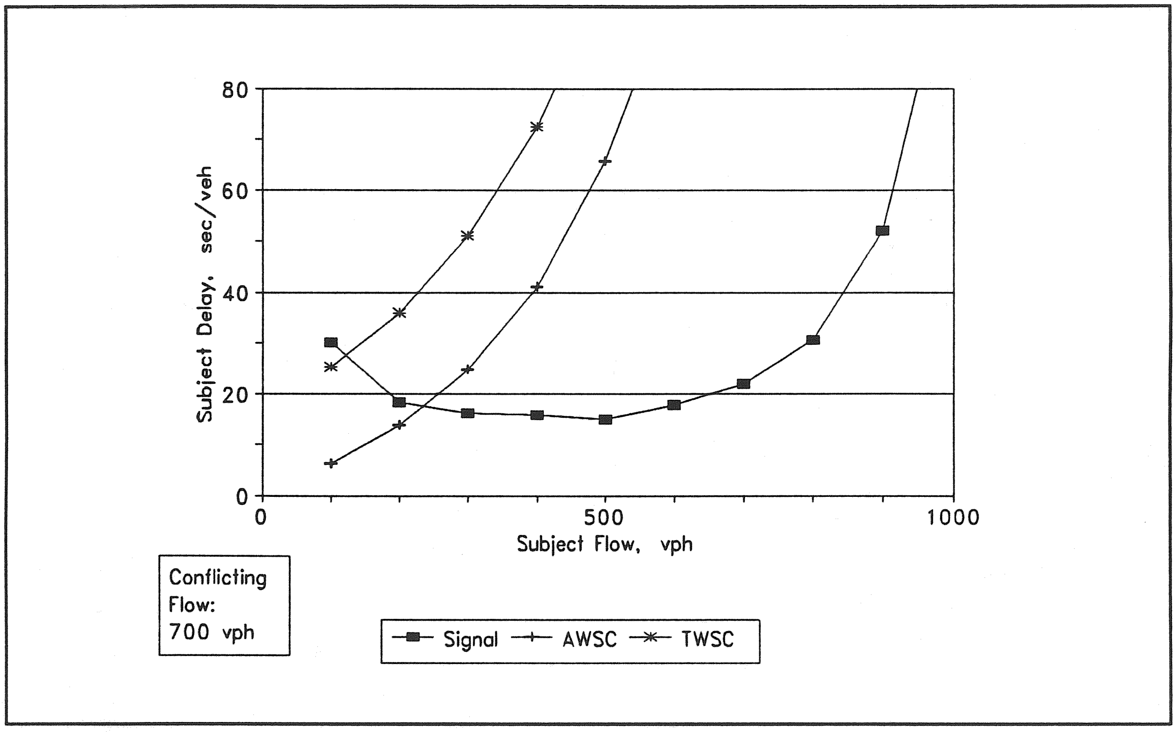

Figure 23. Subject Approach Delay As A Function of Subject Approach Flow

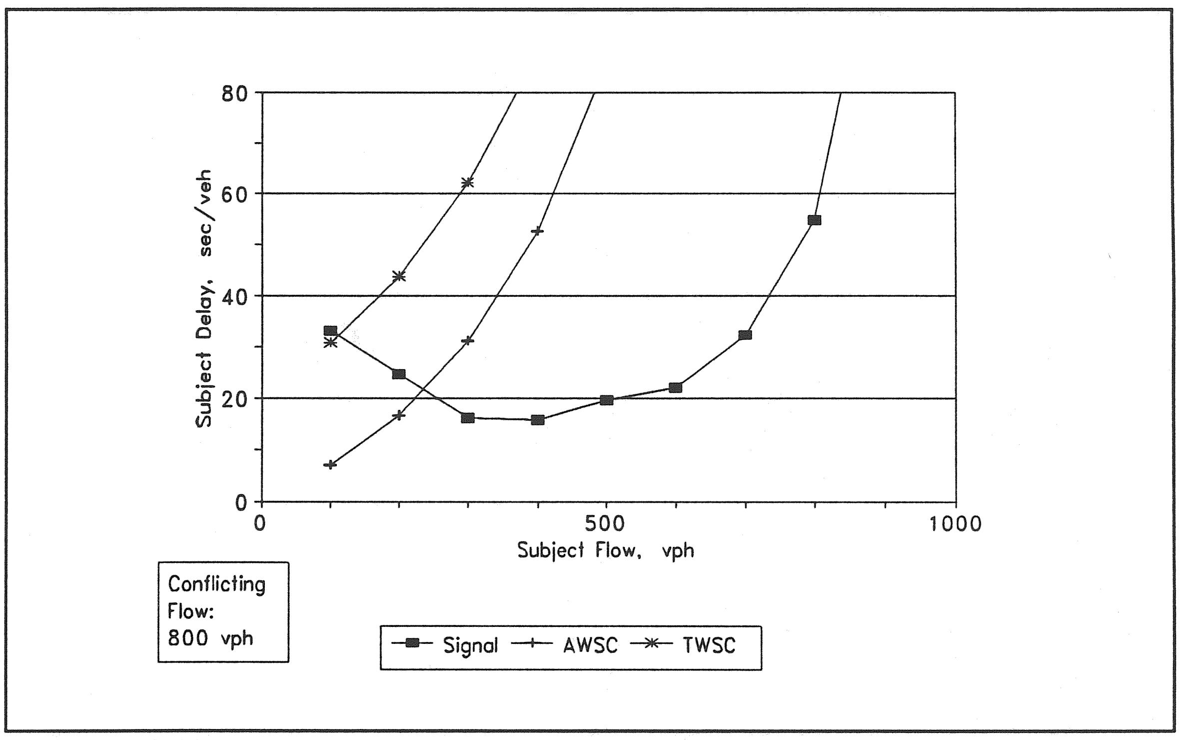

Figure 24. Subject Approach Delay As A Function of Subject Approach Flow

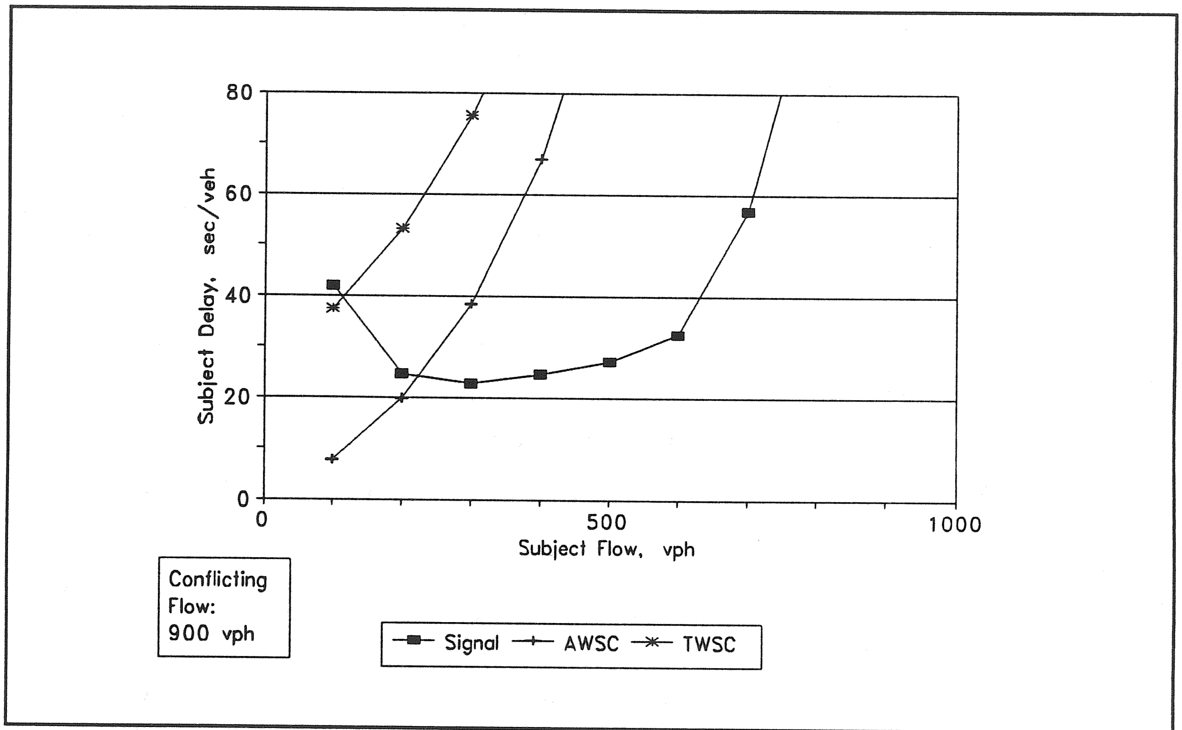

Figure 25. Subject Approach Delay As A Function of Subject Approach Flow

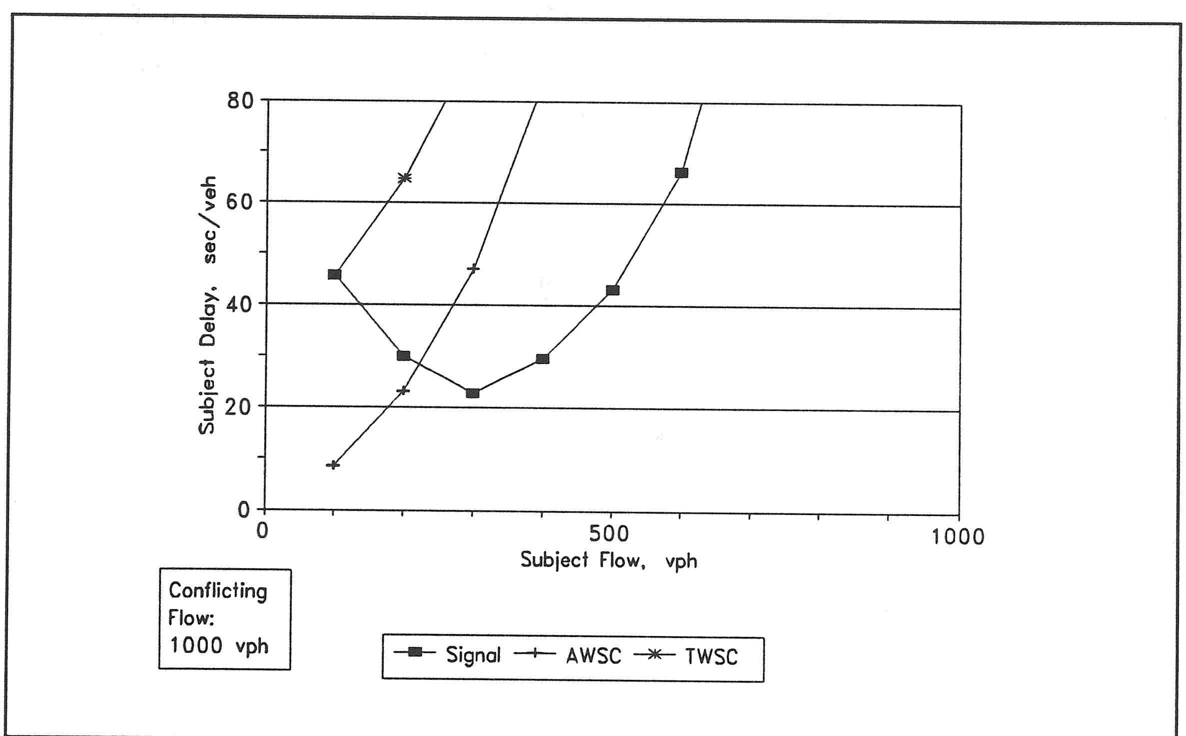

Figure 26. Subject Approach Delay As A Function of Subject Approach Flow

The figures on the following pages show a paired comparison of subject approach delay between the three intersection control types.

Figure 27 compares all-way stop-control and signal control. The figure shows a contour plot of signal delay minus AWSC delay for a range of major and minor street volumes. A negative value indicates that signal delay is less than the AWSC delay and thus the intersection would perform more effectively if it were operated with signal control. A positive value indicates that AWSC delay is less than the signal delay and the intersection would operate more effectvely if it were controlled in all directions by stop signs. There is a clear dividing line between the performance of signal control vs AWSC control. When the minor street volume is less than 500 vph, AWSC is better; when the minor street volume is greater than 500 vph, signal control is better.

Figure 28 compares two-way stop-control and signal control. The figure shows a contour plot of signal delay minus TWSC delay for a range of major and minor street volumes. As before, a negative value indicates that signal delay is less than TWSC delay; a positive value indicates that TWSC is less than signal delay. There is also a clear dividing line between the performance of signal control and TWSC control. When the minor street volume is less than 200 vph, TWSC is better; when the minor street volume exceeds 200 vph, signal control is better. Thus only when minor street volumes are very low (and thus since the major street volumes are not delayed at all), is TWSC control better than signal control.

Figure 29 compares AWSC intersections and TWSC intersections. The figure shows a contour plot of AWSC delay minus TWSC delay for a range of major and minor street volumes. As before, a negative value indicates that AWSC delay is less than TWSC delay; a positive value indicates that TWSC delay is less than AWSC delay. This figure shows that AWSC is nearly always better than TWSC from the standpoint of the subject approach delay.

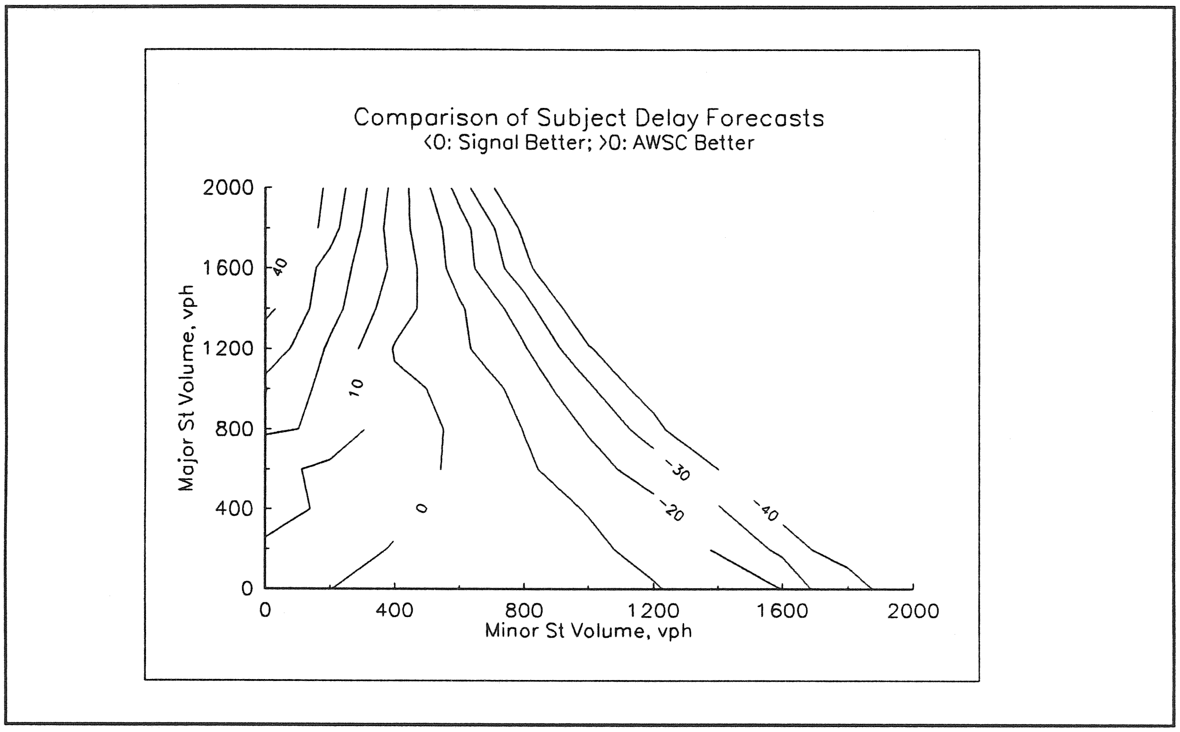

Figure 27. Subject Approach Delay, Signal Delay minus AWSC Delay

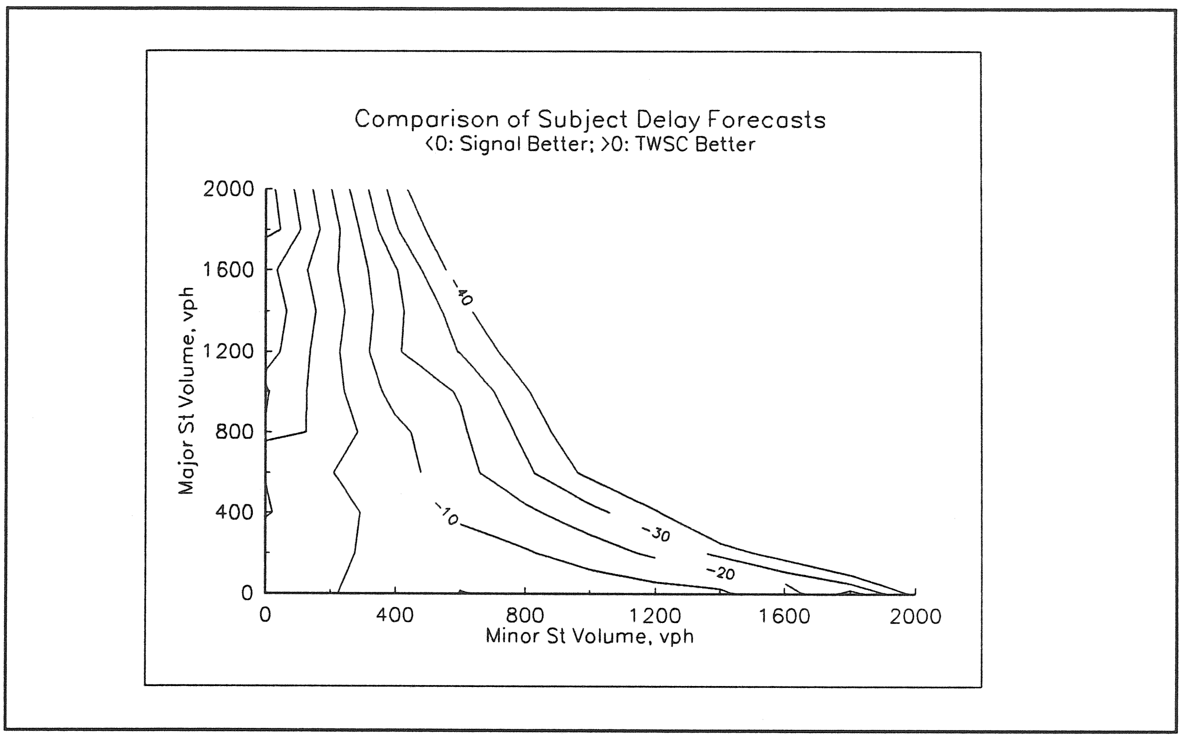

Figure 28. Subject Approach Delay, Signal Delay minus TWSC Delay

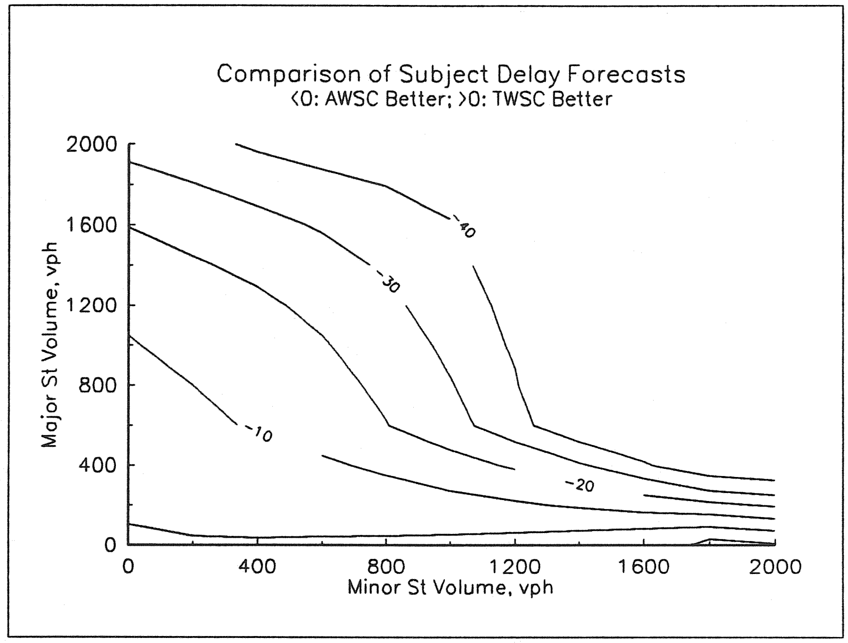

Figure 29. Subject Approach Delay, AWSC Delay minus TWSC Delay

4.4 Comparison of Intersection Delay Estimates

Average delays per vehicle estimated by the simulation models were plotted to compare the performance of the three control types. The graphs shown on the following pages are plots of the average delay for the entire intersection vs subject approach volume, for ten different levels of conflicting flow rates. Examination of these ten graphs show that, as expected, signal control yields minimum delay values for the broadest range of traffic flow rates. The following specific conclusions can be noted:

1. AWSC or TWSC provide optimal control only for subject flow rates less than 100 to 300 vph, depending on the conflicting flow rates.

2. Signal control provides optimal control when subject flow rates exceed 200 to 300 vph, for nearly all ranges of conflicting flow rates.

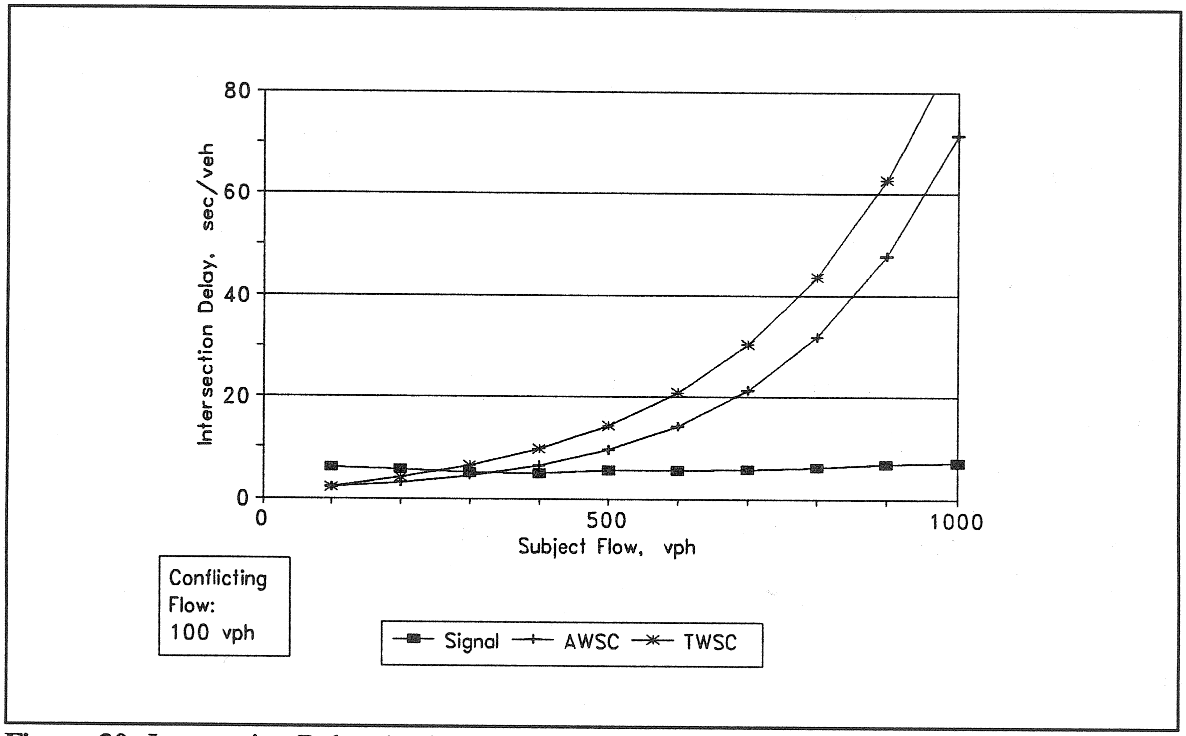

Figure 30. Intersection Delay As A Function Of Subject Approach Flow

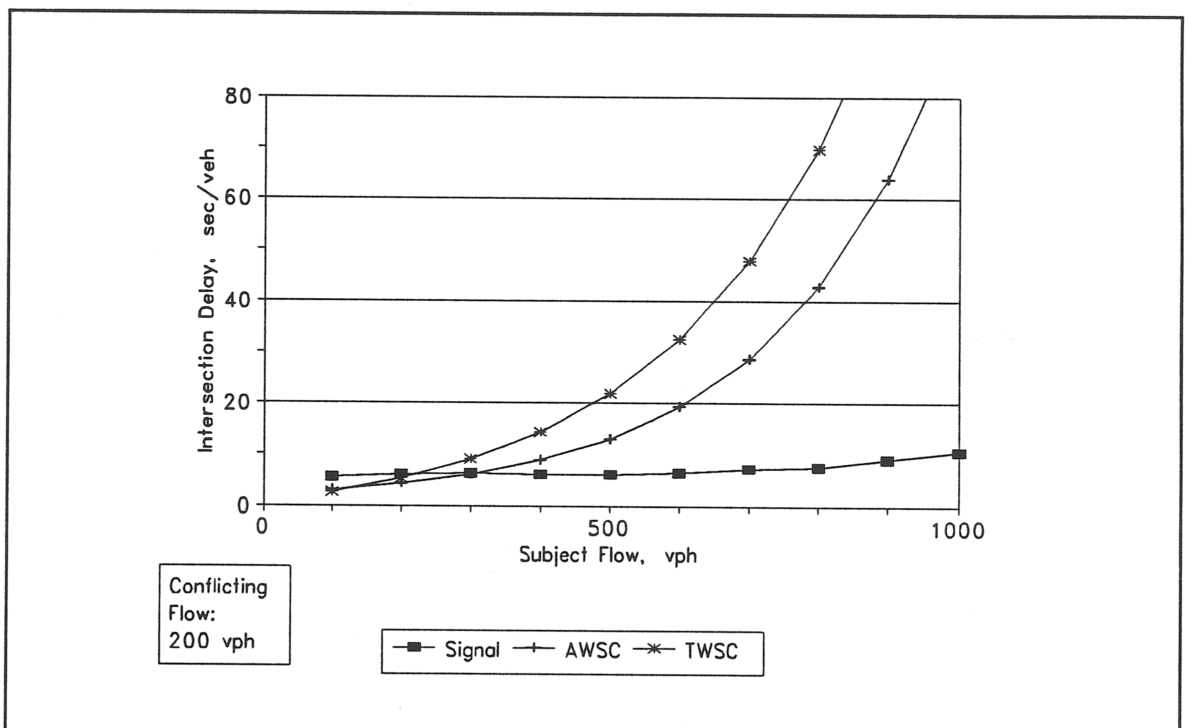

Figure 31. Intersection Delay As A Function Of Subject Approach Flow

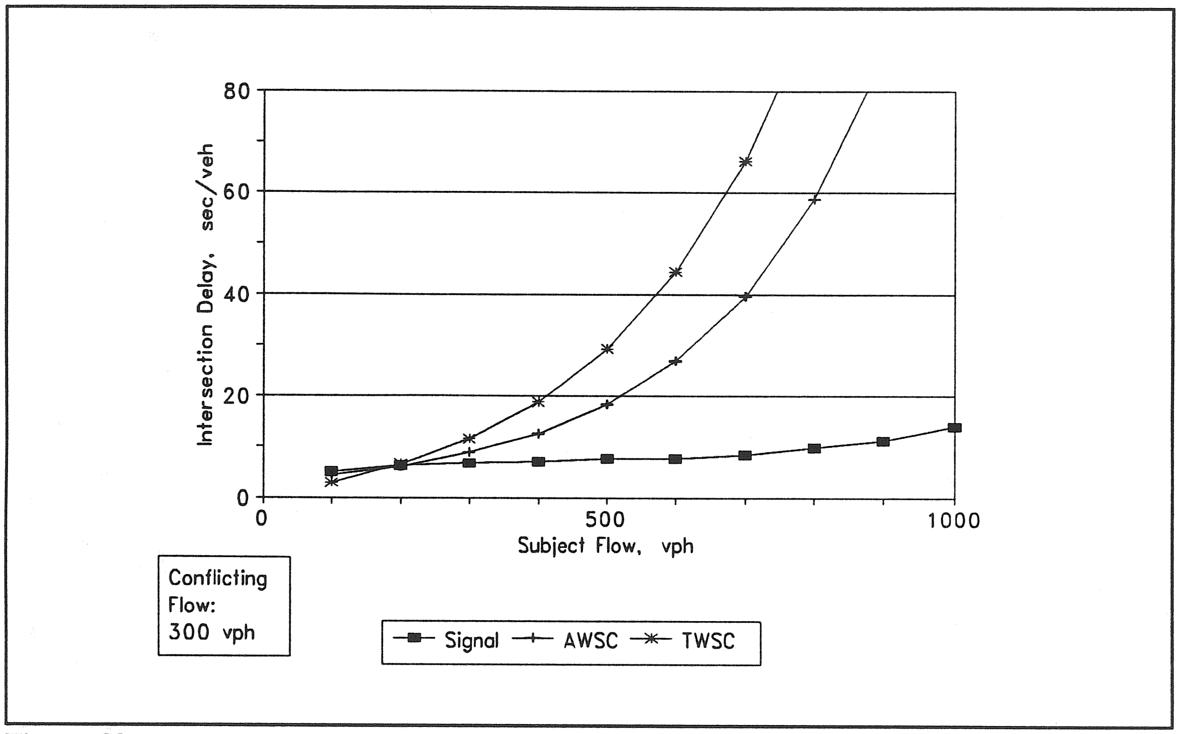

Figure 32. Intersection Delay As A Function Of Subject Approach Flow

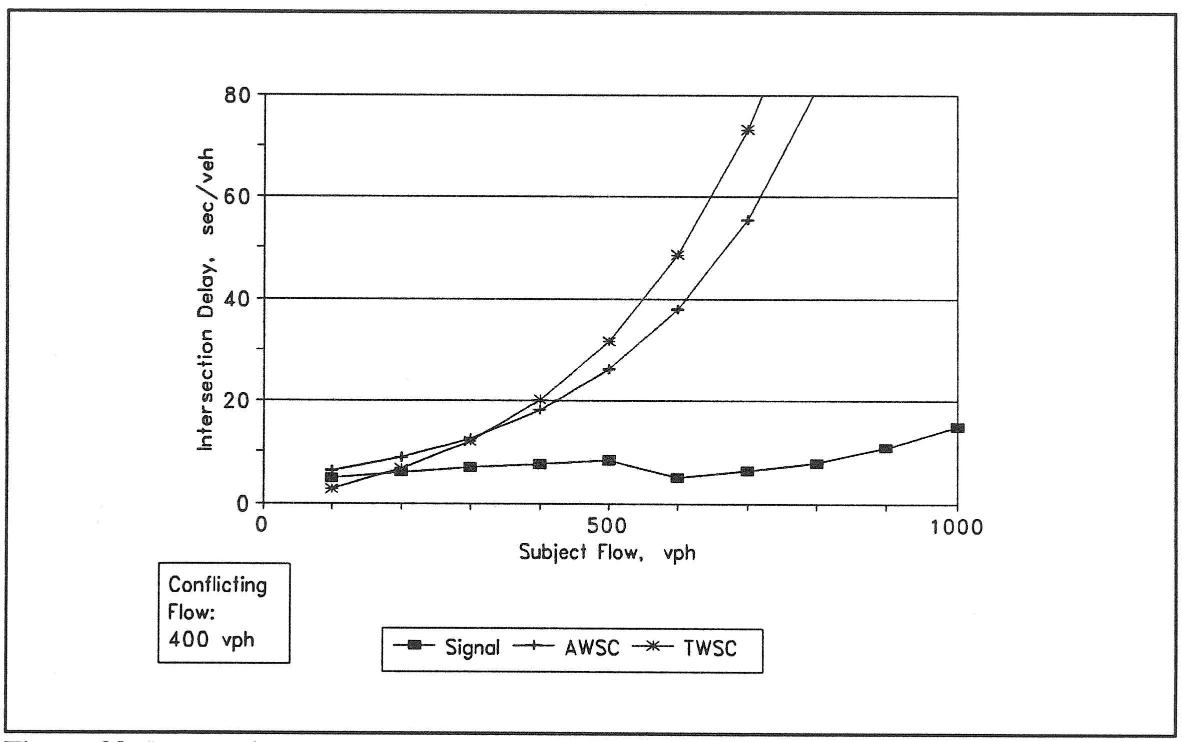

Figure 33. Intersection Delay As A Function Of Subject Approach Flow

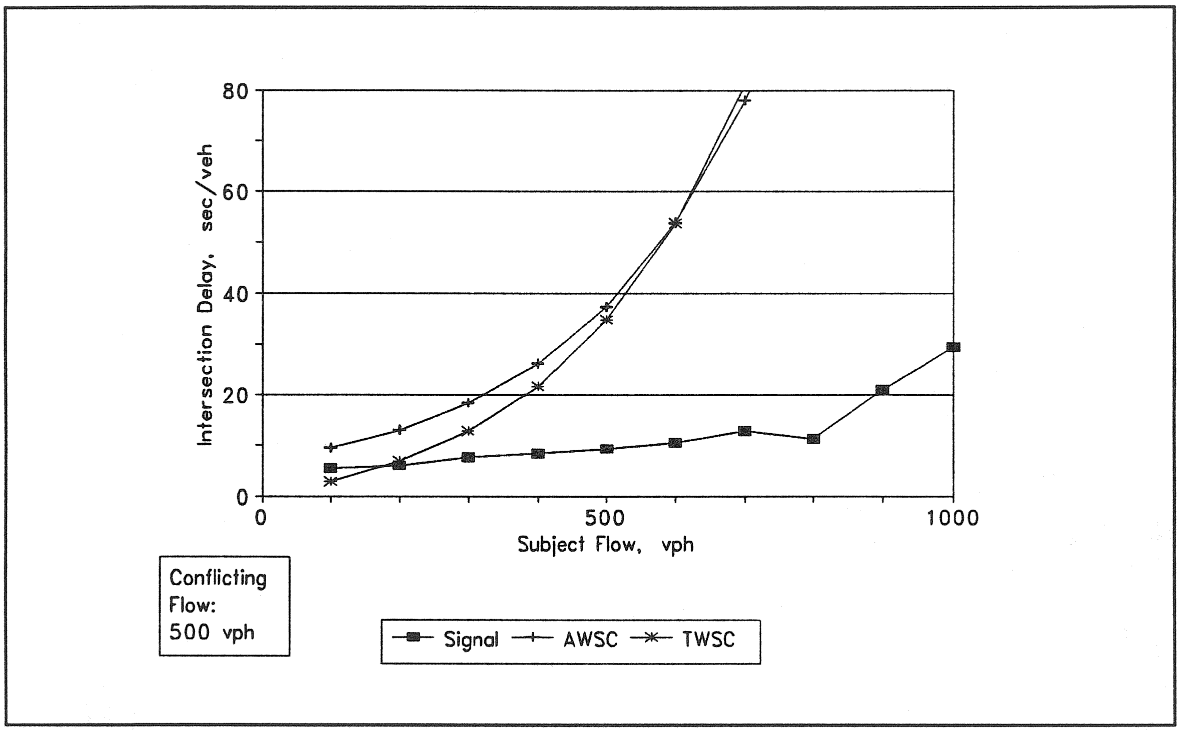

Figure 34. Intersection Delay As A Function Of Subject Approach Flow

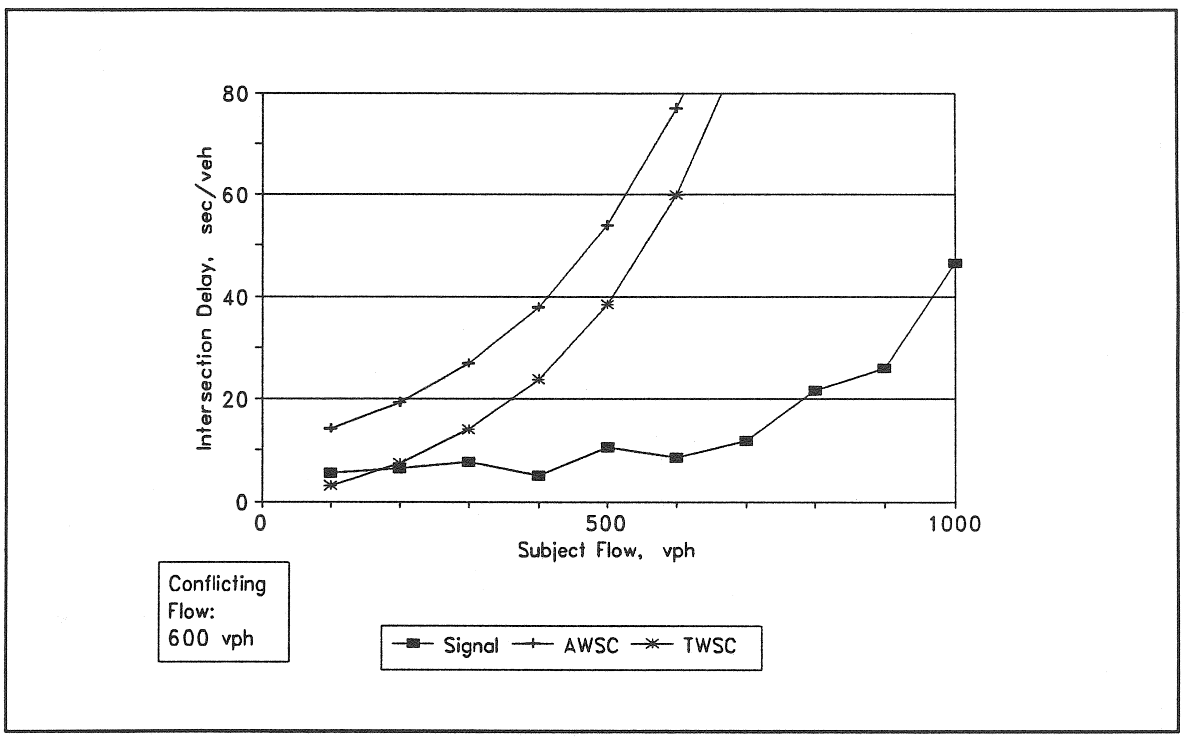

Figure 35. Intersection Delay As A Function Of Subject Approach Flow

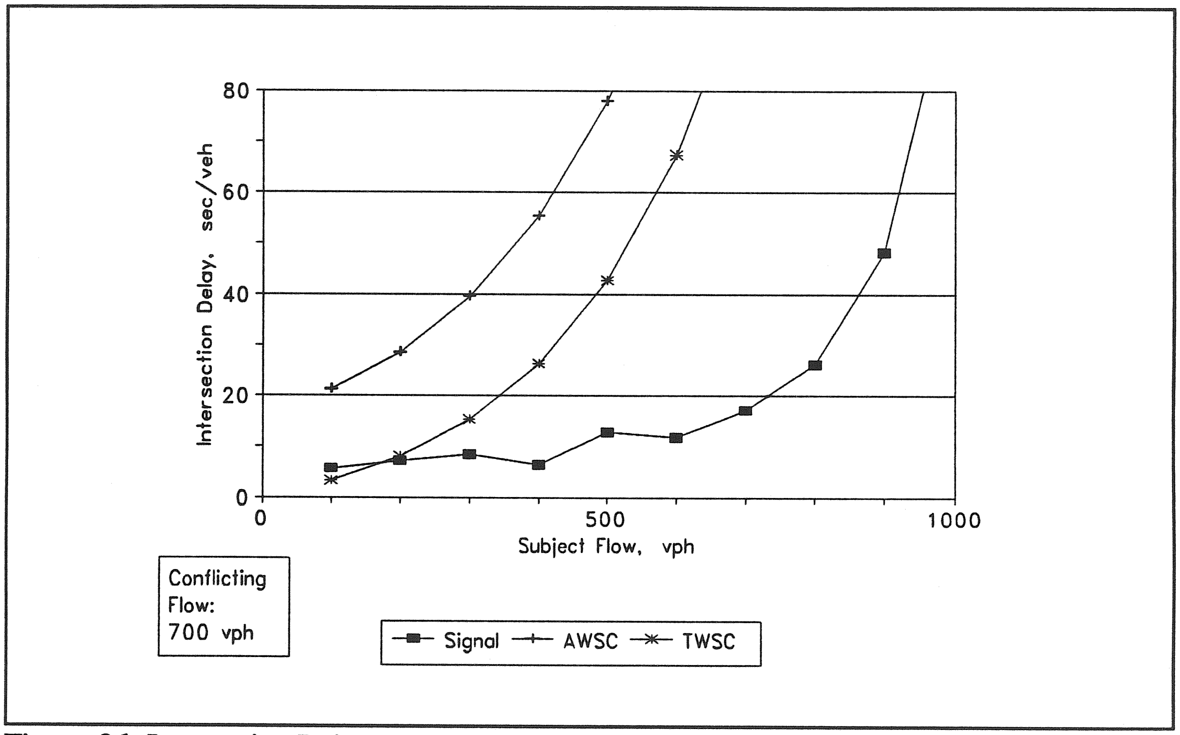

Figure 36. Intersection Delay As A Function Of Subject Approach Flow

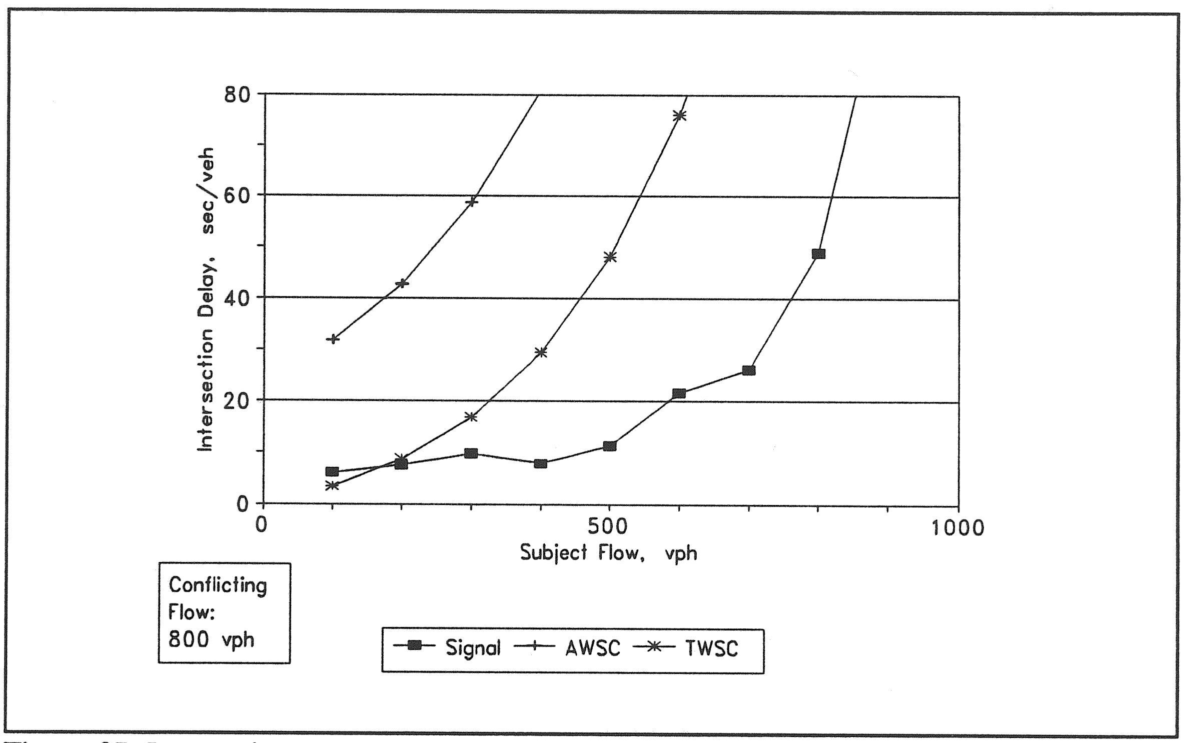

Figure 37. Intersection Delay As A Function Of Subject Approach Flow

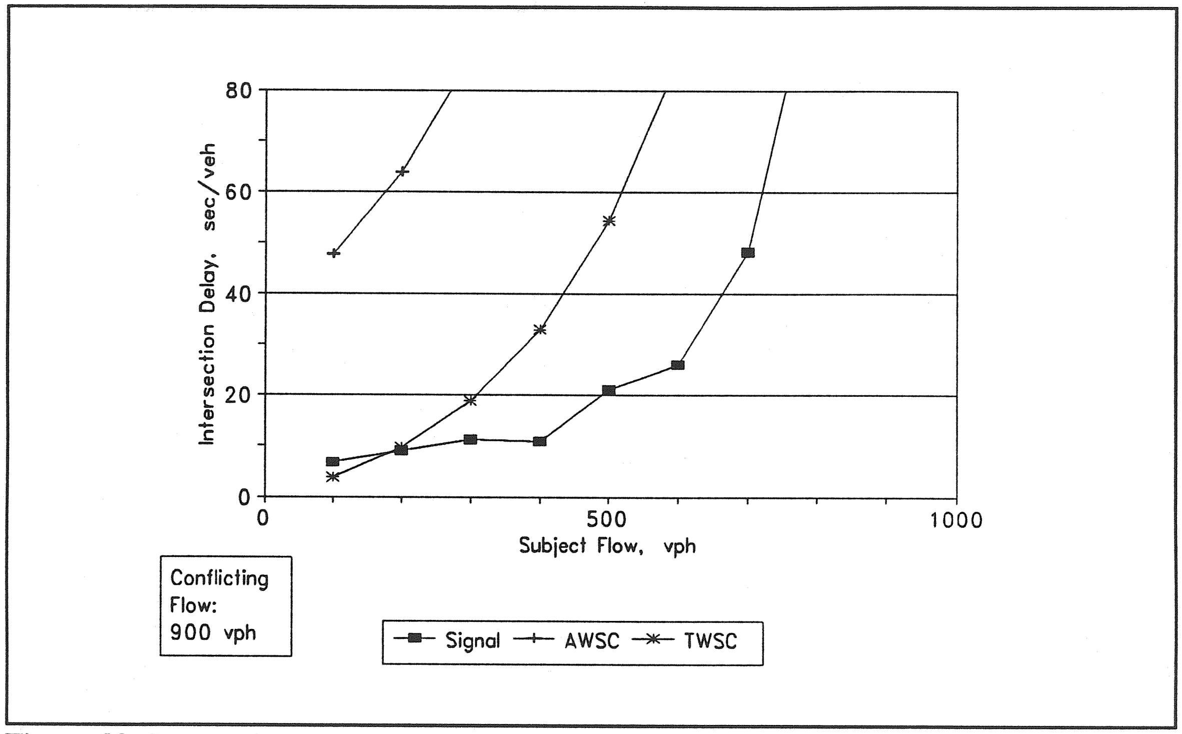

Figure 38. Intersection Delay As A Function Of Subject Approach Flow

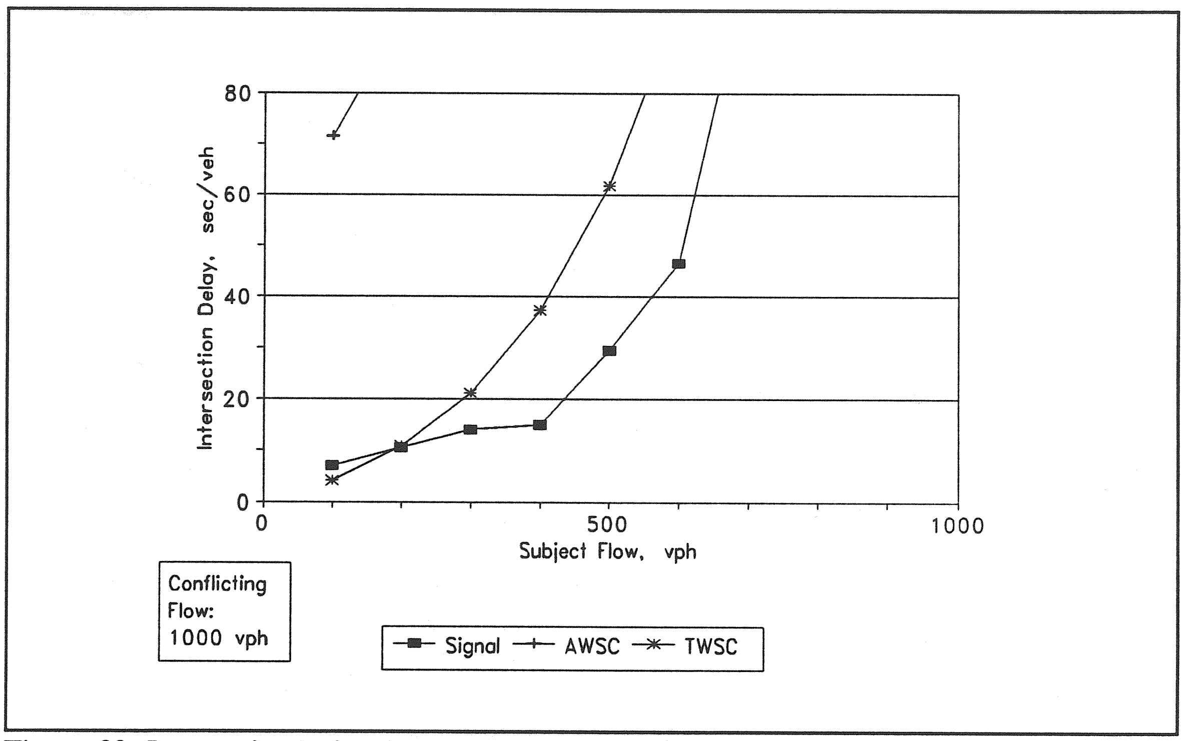

Figure 39. Intersection Delay As A Function Of Subject Approach Flow

The figures on the following pages show a paired comparison of intersection delay between the three intersection control types.

Figures 40 compares all-way stop-control and signal control. The figure shows a contour plot of signal delay minus AWSC delay for a range of major street and minor street volumes. A negative value indicates that signal delay is less than AWSC delay; a positive value indicates that AWSC delay is less than signal delay. Figure 40 shows that AWSC is better than signal control when the sum of the major and minor street flows is less than 400 vph. Signal control is better when the sum of the major and minor street flows exceeds 400 vph.

Figures 41 compares two-way stop-control and signal control. The figure shows a contour plot of signal delay minus TWSC delay for a range of major street and minor street volumes. A negative value indicates that signal delay is less than TWSC delay; a positive value indicates that TWSC delay is less than signal delay. Figure 41 shows that TWSC is better than signal control only when the minor street volume is less than 200 vph. Signal control is better in all other cases.

Figures 42 compares all-way stop-control and two-way stop-control. The figure shows a contour plot of AWSC delay minus TWSC delay for a range of major street and minor street volumes. A negative value indicates that AWSC delay is less than TWSC delay; a positive value indicates that TWSC delay is less than AWSC delay. Figure 42 shows that AWSC and TWSC each have ranges in which they perform better. TWSC is generally better when major street volumes exceed minor street volumes. AWSC is generally better for the opposite case, when minor street volumes equal or exceed major street volumes.

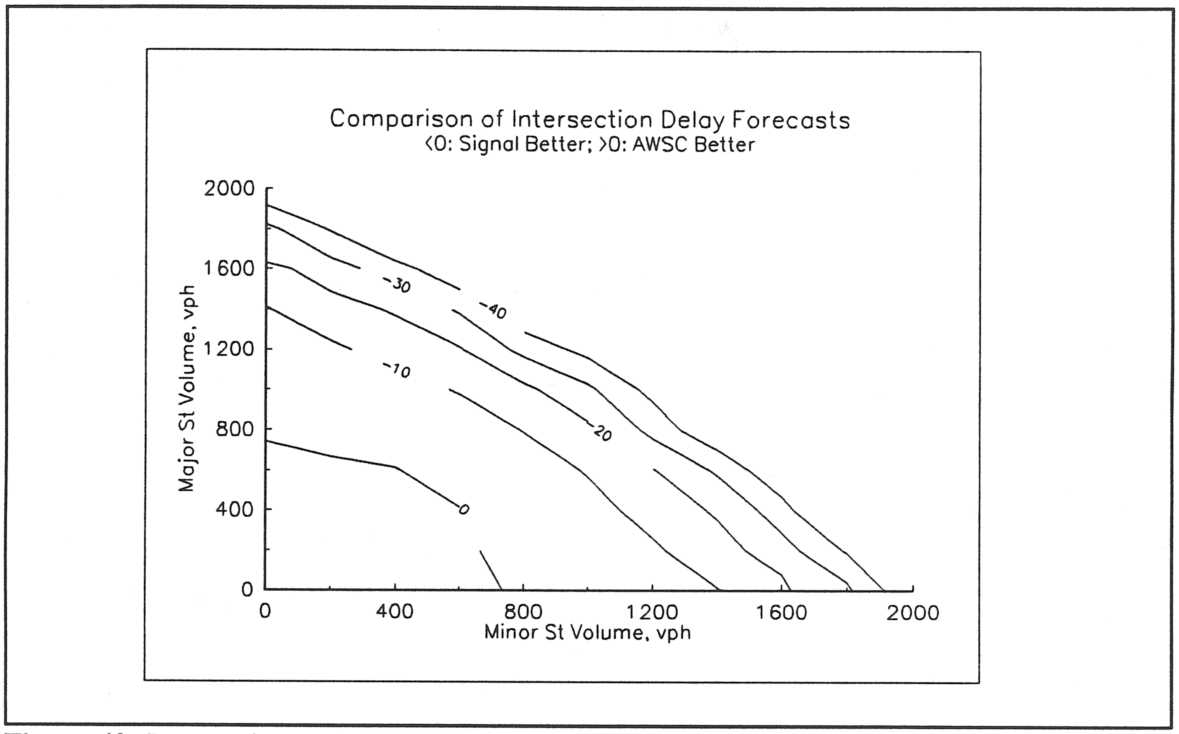

Figure 40. Intersection Delay, Signal Delay Minus AWSC Delay

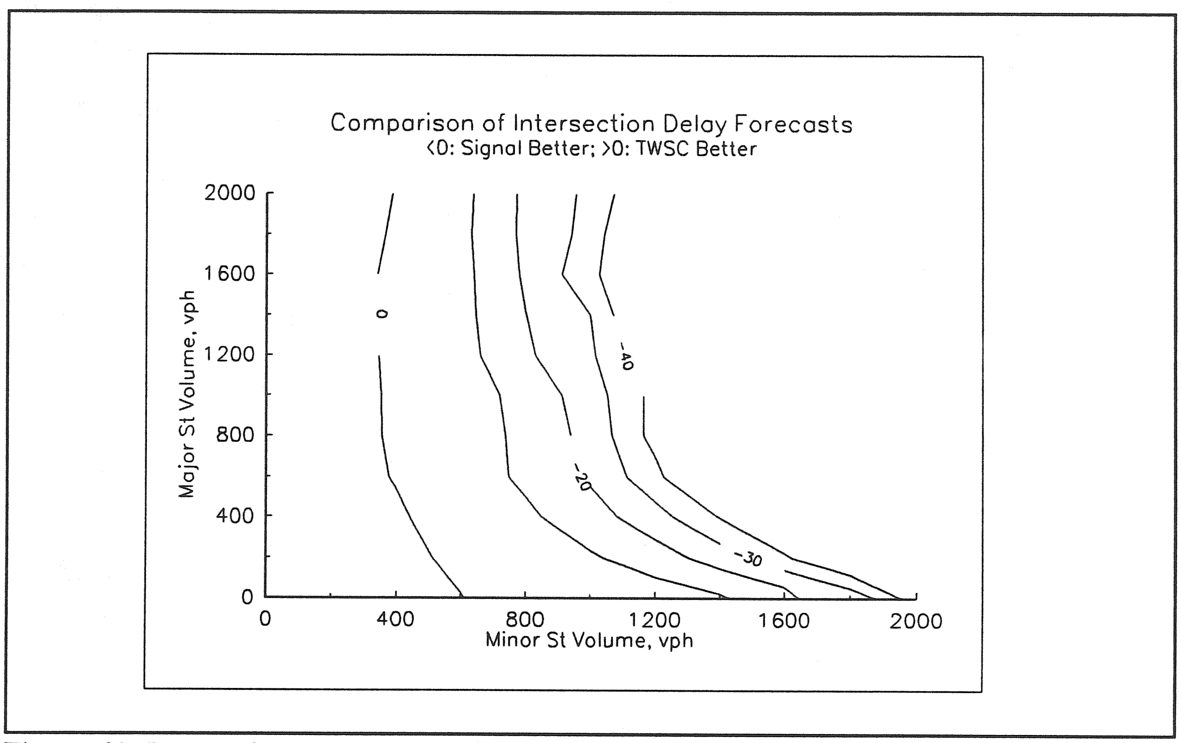

Figure 41. Intersection Delay, Signal Delay Minus TWSC Delay

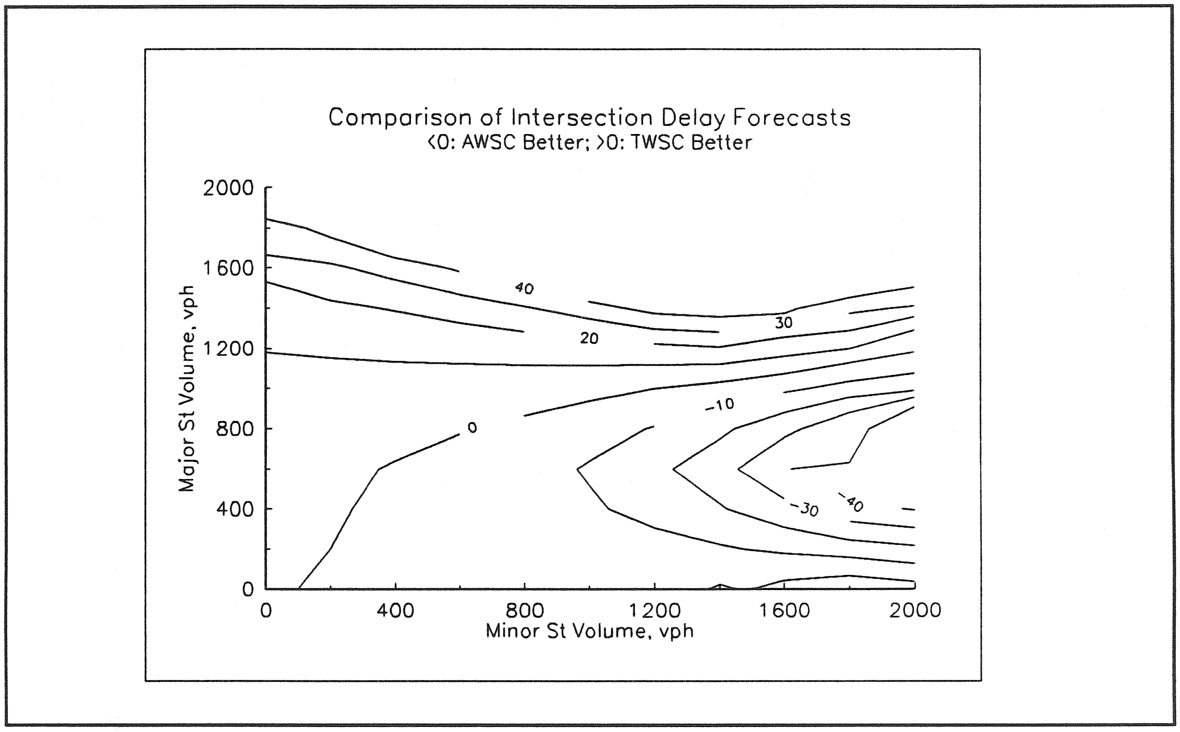

Figure 42. Intersection Delay, AWSC Delay Minus TWSC Delay

4.5 Determination of Optimal Control For Different Flow Rates Based On Subject Approach Delay

In the previous section, the performance of the three control types were compared using delay as the measure of effectiveness. The control strategy determined which yielded minimum delay for a given set of traffic flow rates was identified. But often the delay estimates are relatively close and either drivers are not able to discern such minor differences or the accuracy of the models means that the forecasted differences are not significant. Figures 43 and 44 compare the delay estimates with consideration given to the following issues. First, the region of traffic flows is identified when all three control types yield relatively low delays and all would be judged to be performing at LOS A or B. Second, those regions are identified in which one type is significantly better than the other two types, either five seconds better or ten seconds better. Third, those regions are identified in which two types are significantly better than the third.

In Figure 43, a five second difference in the delay estimates is assumed to be a significant difference. Here, one would judge that all three control types would be appropriate when the sum of the major and minor street flows is less than about 700 to 800 vph. In this case, each control type would yield LOS A or B. When major street flows are less than 300 to 400 vph, one would judge that AWSC would be the best control type. When major street flows are between 300 and 600 vph, both signal and AWSC control would yield about the same performance. When major street flows are above 600 to 700 vph, signal control is optimal.

In Figure 44, a ten second difference in the delay estimates is assumed to be a significant difference. Here, one would judge that all three control types would be appropriate when the sum of the major and minor street flows is less than about 700 to 800 vph. In this case, each control type would yield LOS A or B. When major street flows are less than 300 to 400 vph, one would judge that AWSC would be the best control type. When major street flows are between 300 and 700 vph, both signal and AWSC control would yield about the same performance. This is slighly higher than for the more restrictive 5 second criterion. When major street flows are above 700 to 800 vph, signal control is optimal.

The analysis presented here begins to show traffic flow regions in which one can make judgements about the most optimal intersection control type.

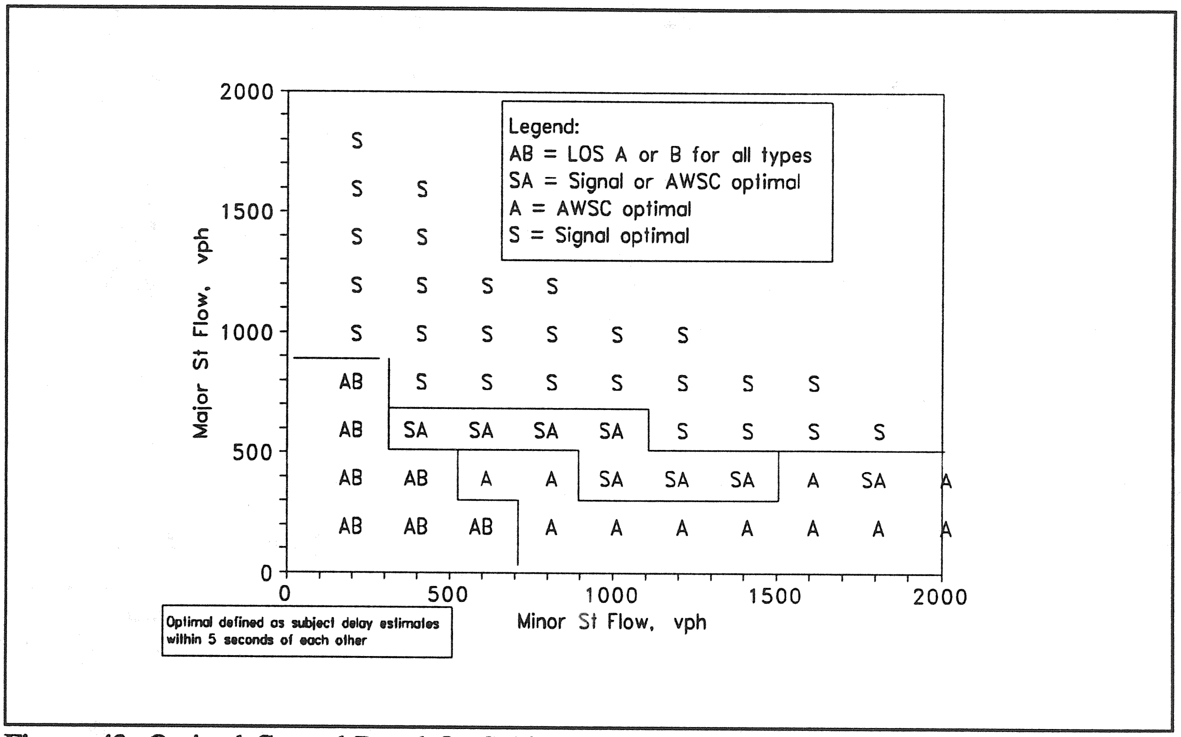

Figure 43. Optimal Control Based On Subject Approach Delay

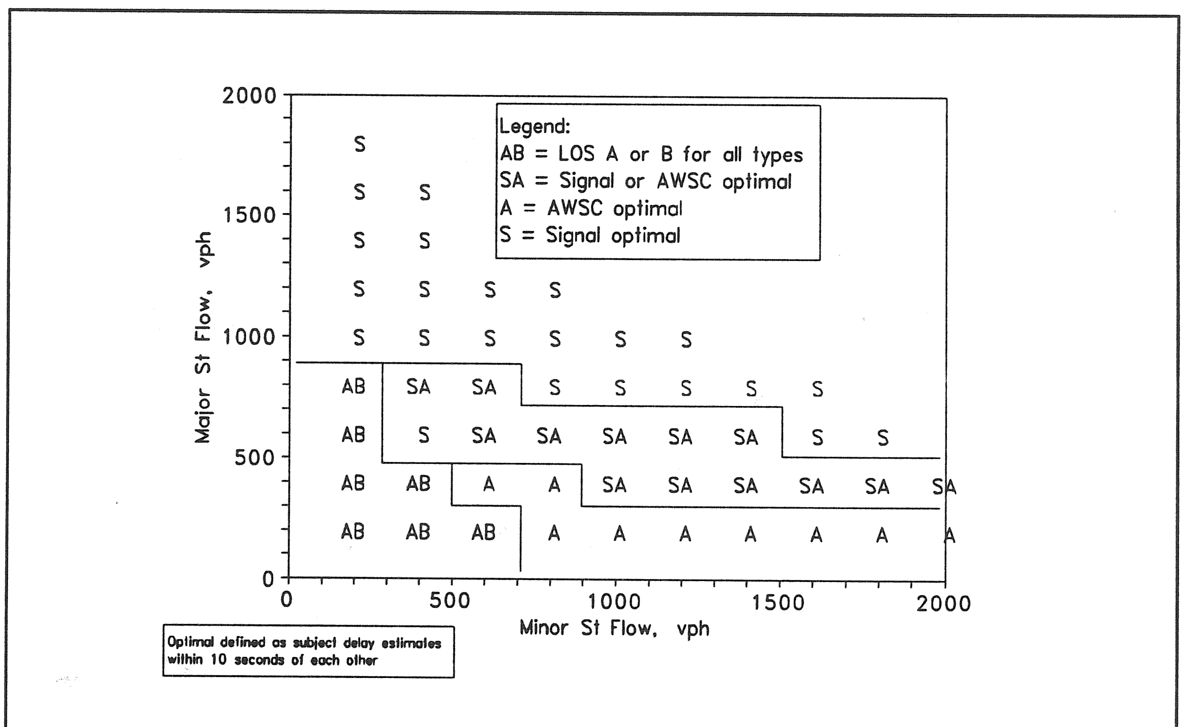

Figure 44. Optimal Control Based On Subject Approach Delay

4.6 Determination of Optimal Control For Different Flow Rates Based On Intersection Delay

In this section, intersection delay estimates are compared. Figures 45 and 46 compare the delay estimates with consideration given to the following issues. First, the region of traffic flows is identified when all three control types yield relatively low delays and all would be judged to be performing at LOS A or B. Second, those regions are identified in which one type is significantly better than the other two types, either five seconds better or ten seconds better. Third, those regions are identified in which two types are significantly better than the third.

In Figure 45, a five second difference in the delay estimates is assumed to be a significant difference. Here one would judge that all three control types would be appropriate when the sum of the major and minor street flows is less than about 1200 to 1400 vph. In this case, each control type would yield LOS A or B. When major street flows are less than 500 vph and minor street flows exceed 1200 vph, either signal or TWSC would be optimal. When major street flows exceed 600 to 700 vph, signal control is optimal.

In Figure 46, a ten second difference in the delay estimates is assumed to be a significant difference. Here one would judge that all three control types would be appropriate when the sum of the major and minor street flows is less than 1400 to 1500 vph. In this case, each control type would yield LOS A or B. When major street flows are less than 700 vph and minor street flows exceed 1100 vph, either signal or TWSC would be optimal. When major street flows exceed 700 vph, signal control is optimal.

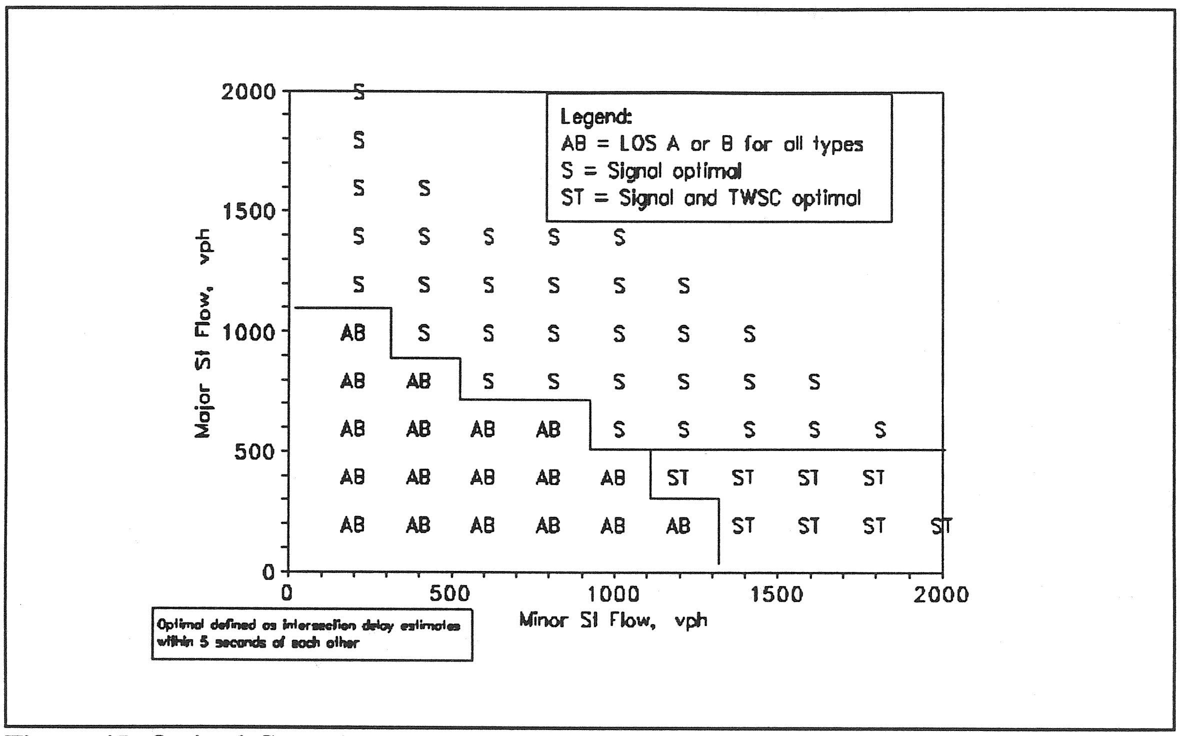

Figure 45. Optimal Control Based On Intersection Delay

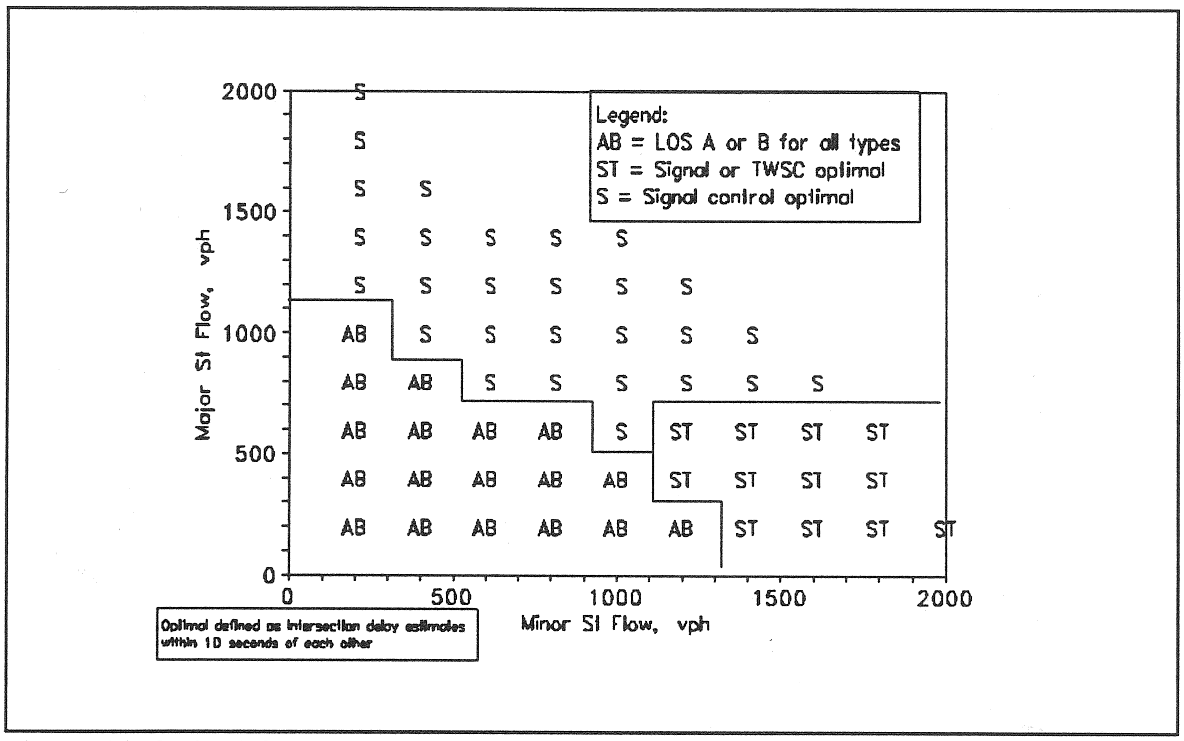

Figure 46. Optimal Control Based On Intersection Delay

5. SIMULATION OF MULTI-LANE APPROACH INTERSECTIONS

In this chapter, the results of the simulation runs for multi-lane approach intersections will be discussed. The simulation methodology is described in the first section. The simulation results are presented in the second section. Comparison of the subject approach and intersection delay estimates are given in the third section.

5.1 Methodology

To compare the performance of an intersection with different kinds of control, simulation runs were made for a range of traffic flow conditions. Flow rates ranged from 100 vph to 1000 vph on each approach with no turning movements. Two lanes were assumed for each approach. However, only two kinds of intersection control were compared: signal control and AWSC control. Unfortunately, the TWSC intersection simulation model cannot consider multi-lane approaches.

5.2 Simulation Results

The results of the intersection simulation are given in Figures 47 through 56.

Figures 47 through 51 show a comparison of subject approach delays for signal control and AWSC for a range of subject approach and conflicting approach flow rates. Figures 52 through 56 show a comparison of intersection delays for signal control and AWSC for the same range of flow rates.

5.3 Comparison of Delay Estimates

The complexity of traffic operations at multi-lane approach intersections clearly argues for signalized intersection control. This is supported in part by recent studies of AWSC intersections which found that [4, p 13]:

> "Unlike other highway facilities, increasing the number of lanes does not necessarily result in a corresponding increase in the capacity of an approach. This fact results from the nature of traffic flow at an AWSC intersection. For single lane approach intersections operating at capacity, a two-phase operation results with traffic on opposing approaches flowing simultaneously. ... However, for multi-lane approaches, the nature of the operation is different. The addition of lanes, particularly on the opposing and conflicting approaches, introduces uncertainty among

> drivers such that a four-phase operation can result. That is, traffic on each approach flows as a group. ... This means that the potential increase in capacity to be gained from additional lanes is offset by the increased uncertainty that results from each driver deciding whether it is his or her turn. ... [Thus], at best, the addition of approach lanes may sligthly increase the capacity of the intersection."

These conclusions are supported by the figures on the following pages. AWSC intersections yield lower delay than for signal control only for the following conditions. First, subject approach delay is lower when subject approach flow is less than 300 to 400 vehicles per hour; second, intersection approach delay is lower only when subject approach flow is less than 400 vehicles per hour and conflicting flow is less than 300 to 400 vehicles per hour.

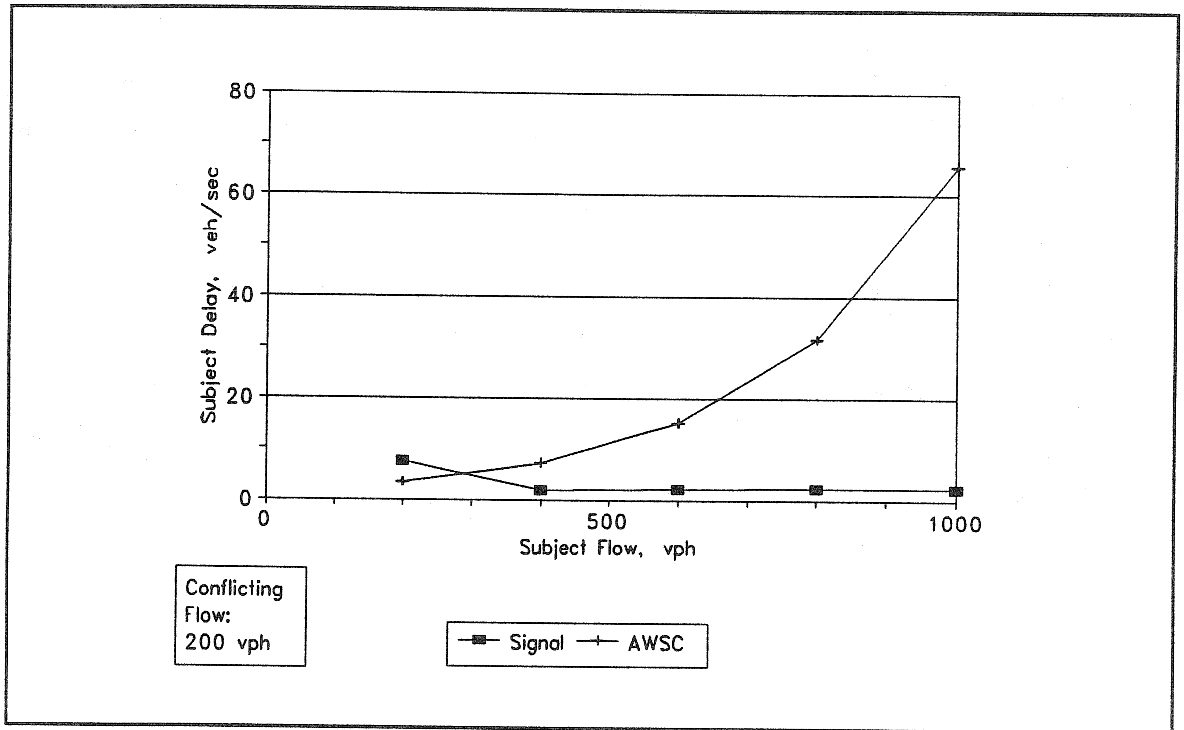

Figure 47. Subject Approach Delay As A Function of Subject Approach Flow

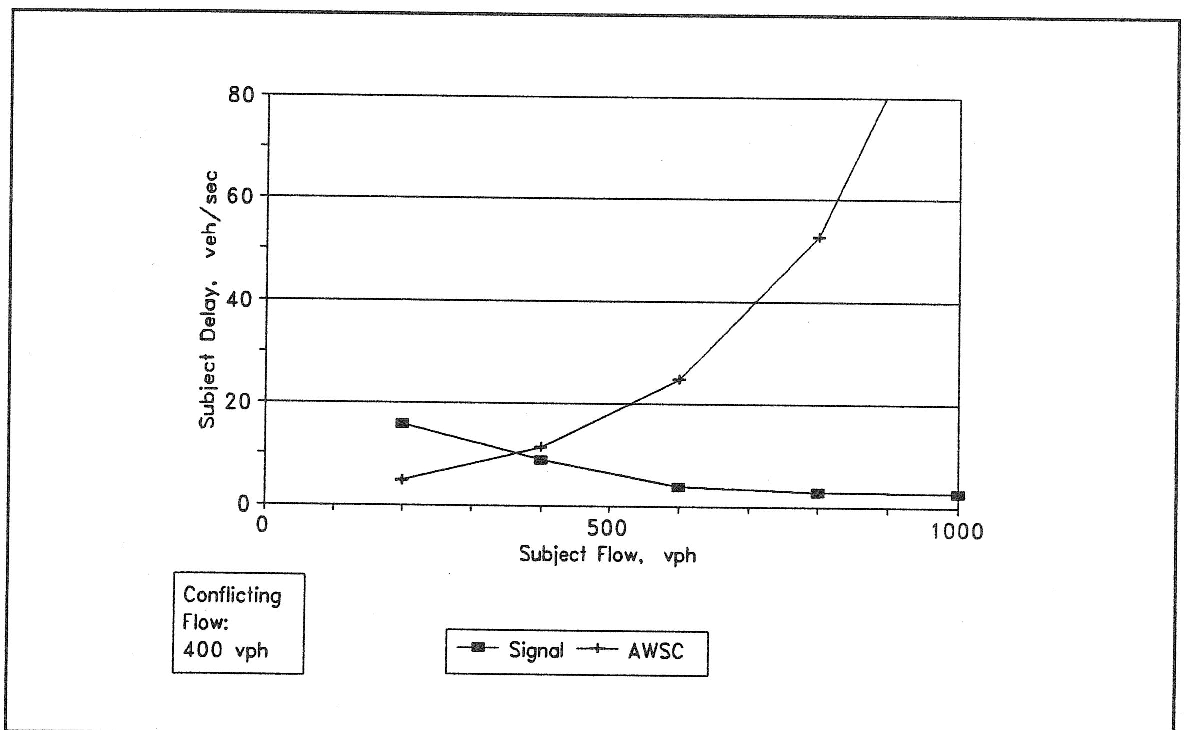

Figure 48. Subject Approach Delay As A Function of Subject Approach Flow

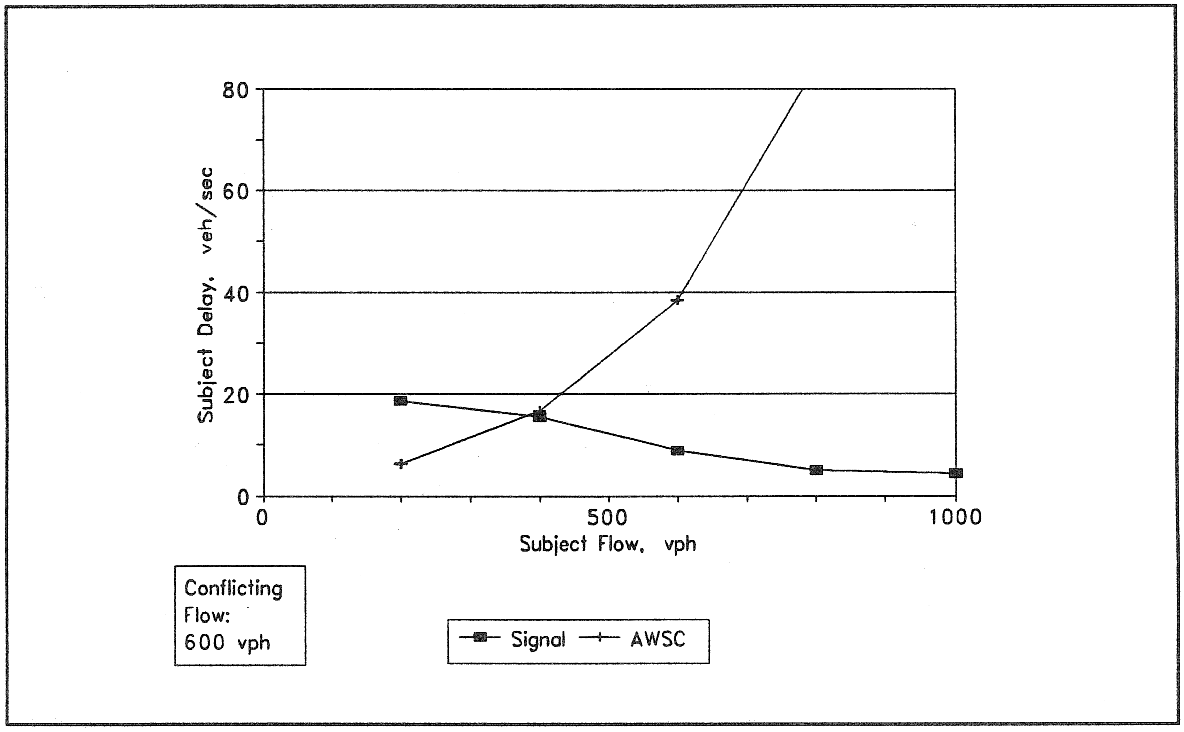

Figure 49. Subject Approach Delay As A Function of Subject Approach Flow

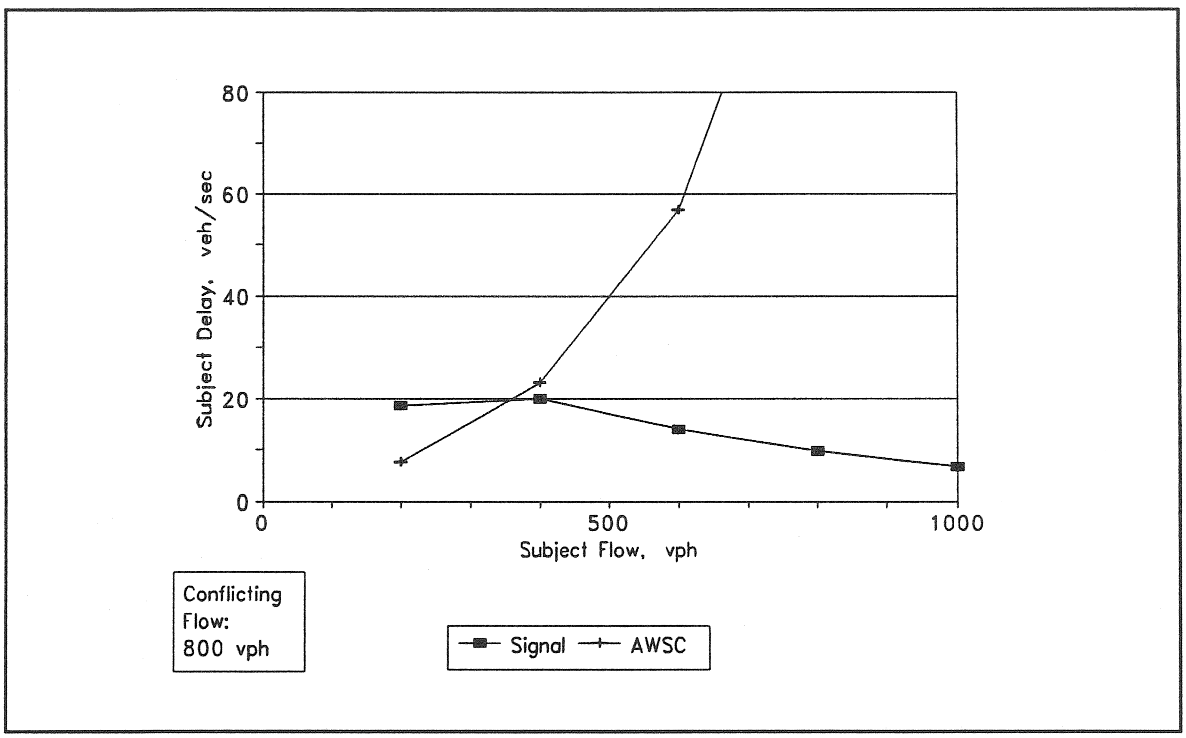

Figure 50. Subject Approach Delay As A Function of Subject Approach Flow

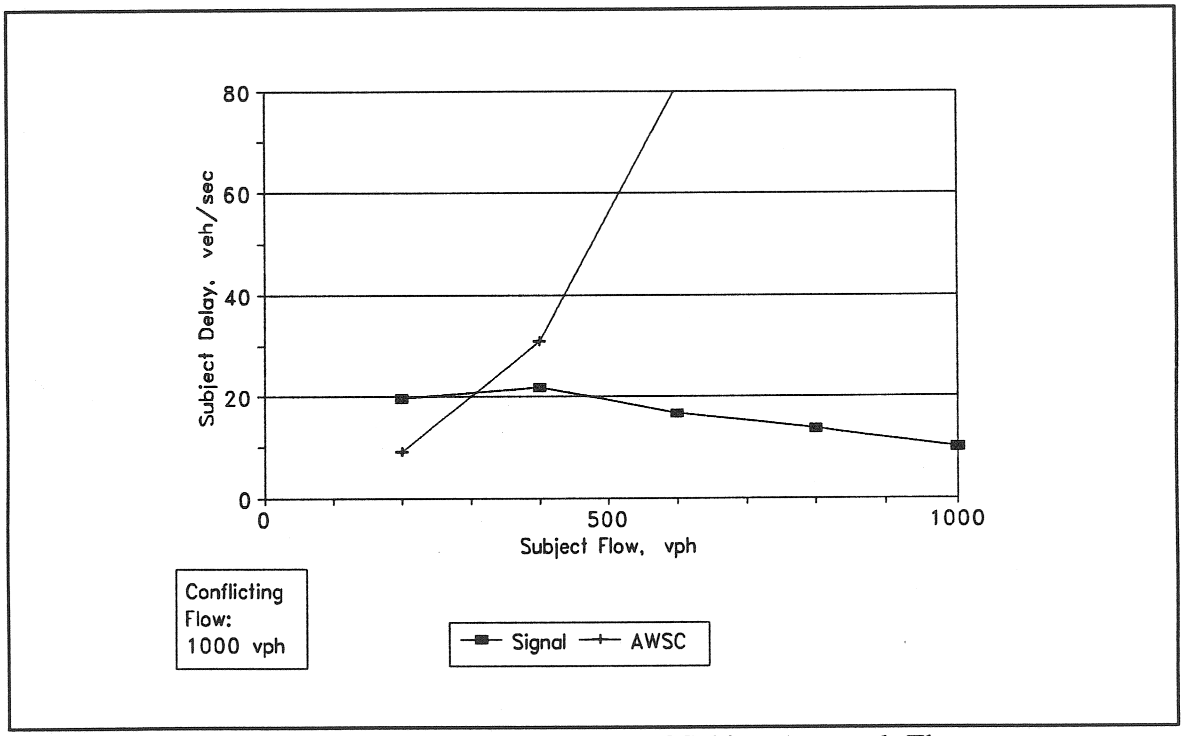

Figure 51. Subject Approach Delay As A Function of Subject Approach Flow

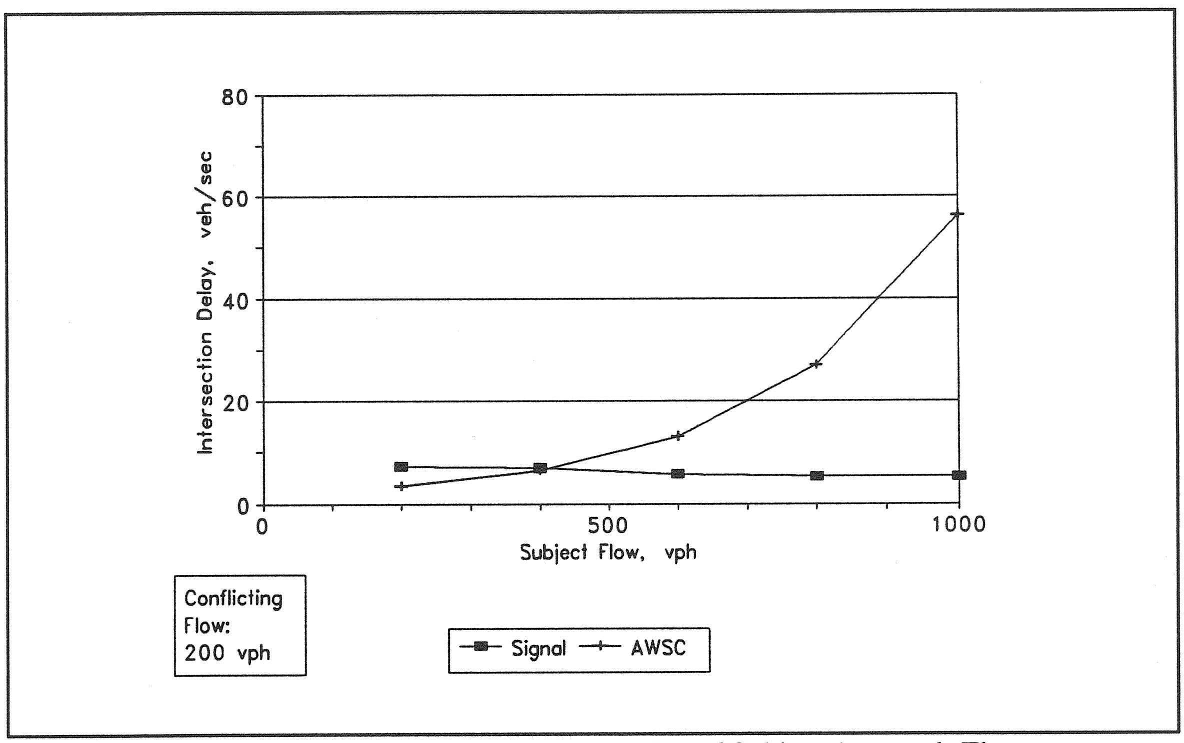

Figure 52. Intersection Approach Delay As A Function of Subject Approach Flow

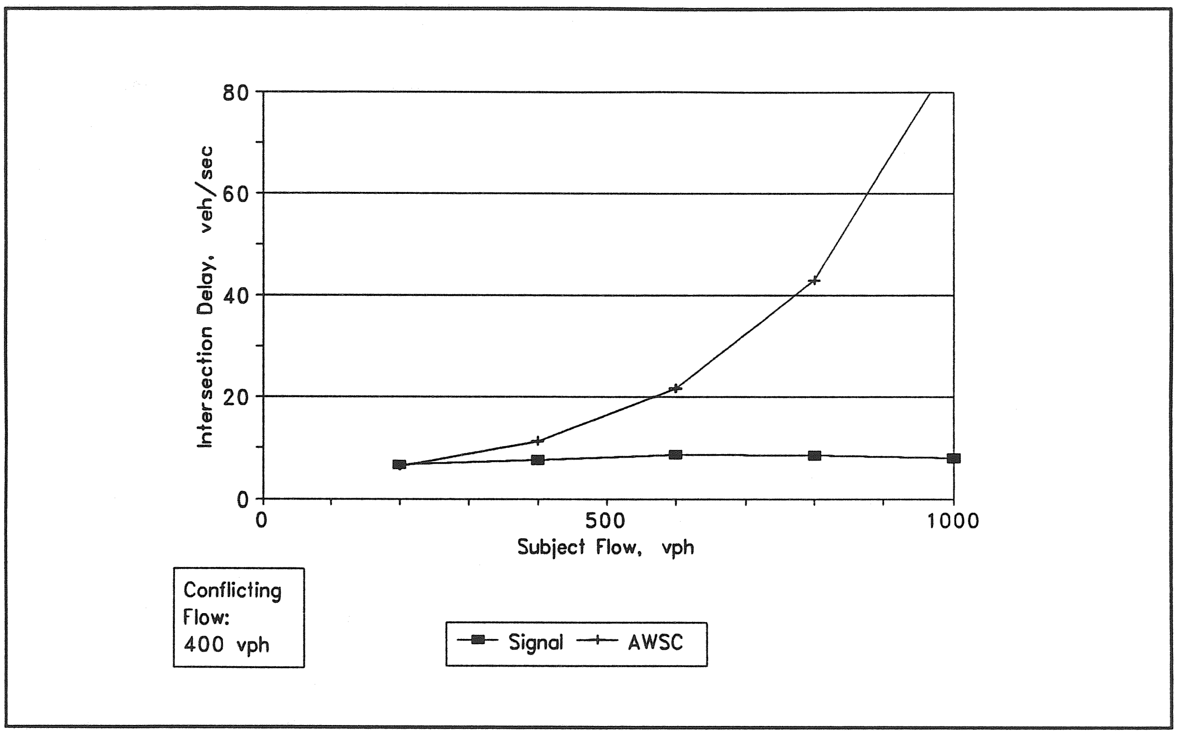

Figure 53. Intersection Approach Delay As A Function of Subject Approach Flow

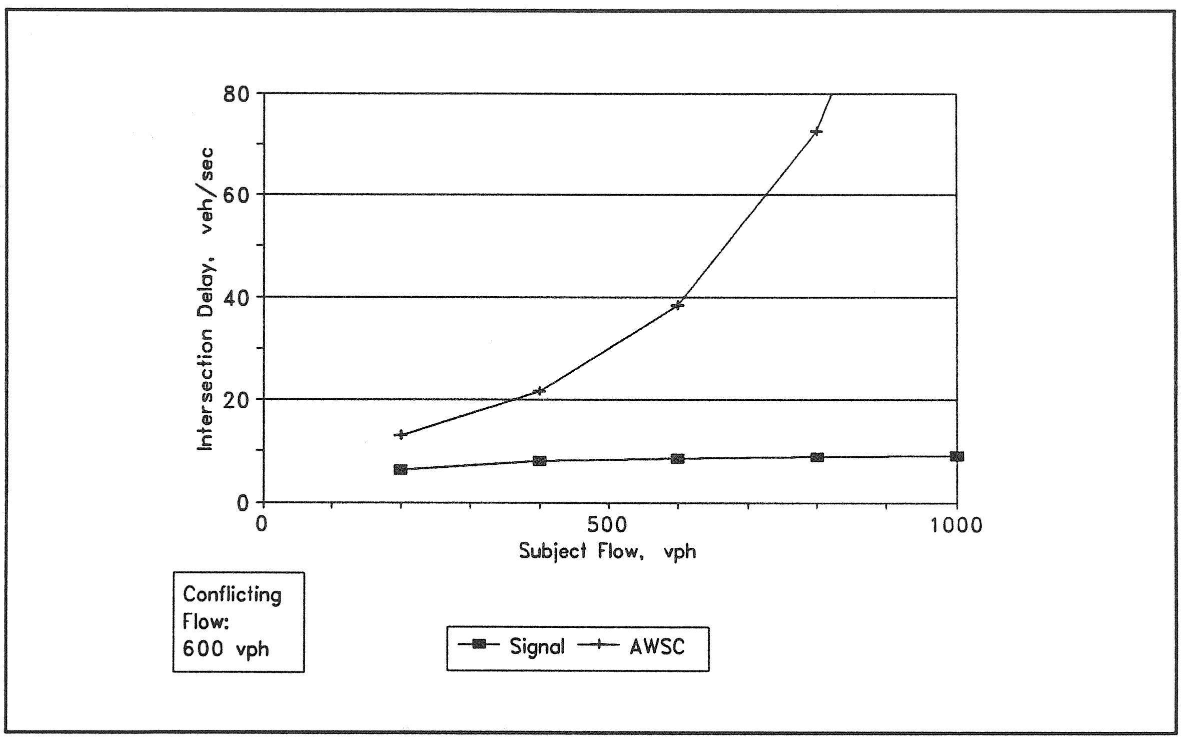

Figure 54. Intersection Approach Delay As A Function of Subject Approach Flow

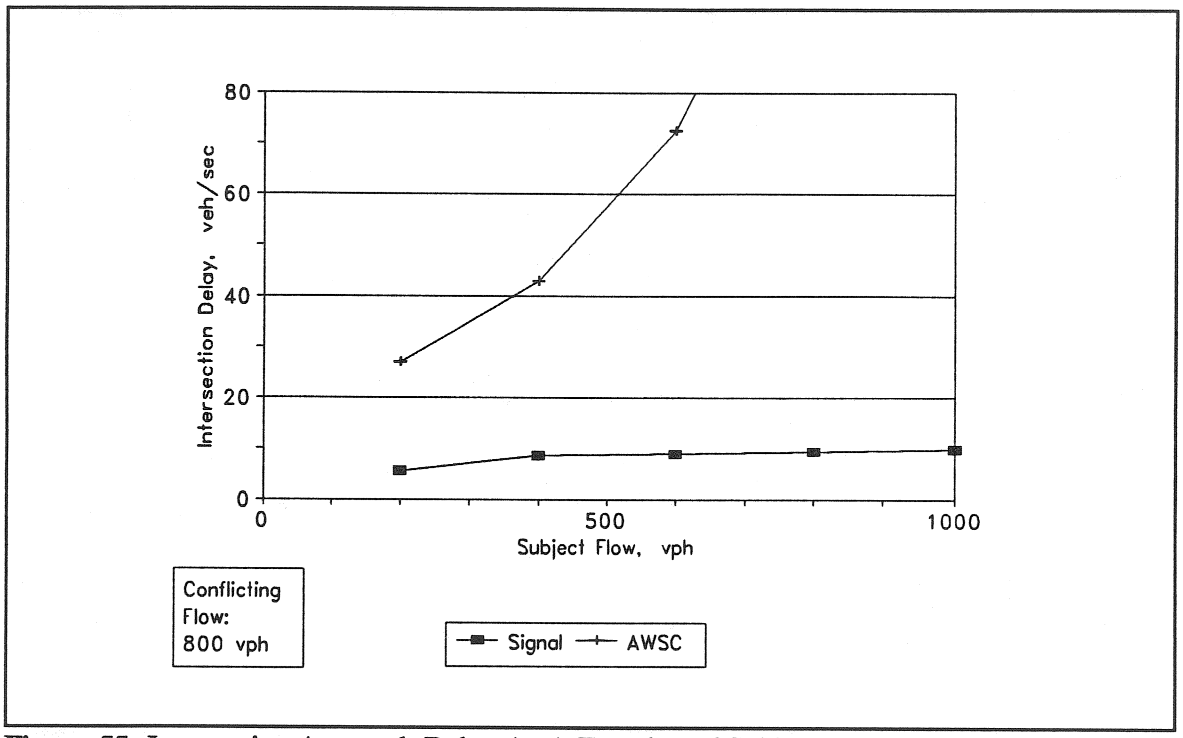

Figure 55. Intersection Approach Delay As A Function of Subject Approach Flow

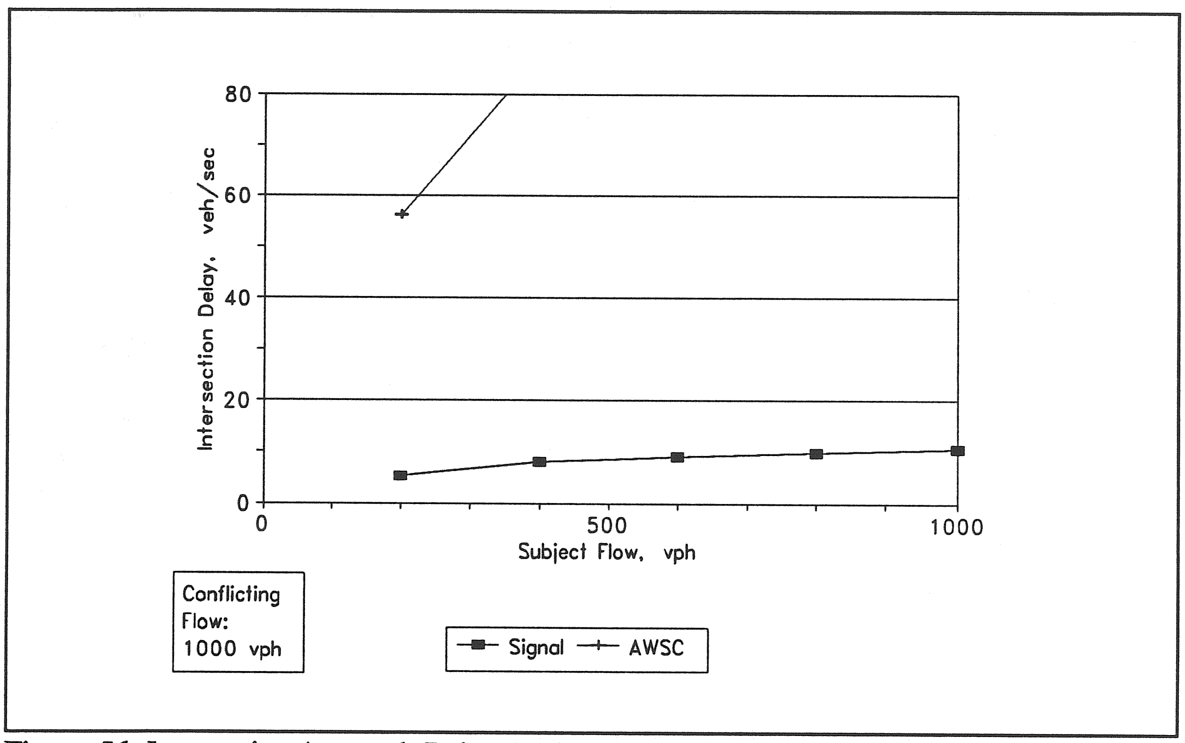

Figure 56. Intersection Approach Delay As A Function of Subject Approach Flow

6. SYNTHESIS OF SIMULATION RESULTS: A RECOMMENDED PROCEDURE

The results of Chapters 4 and 5 have been synthesized into a recommended procedure that can be used by the transportation engineer as a guide in selecting the appropriate kind of control, based on the traffic flow rates and the geometry project for the intersection. The recommended procedure is based on the objective of minimizing vehicle delay for both individual approaches and for the entire intersection. The procedure is based on a refinement of Figures 43 and 45 presented in Chapter 4 and on the discussion presented in Chapter 5.

6.1 Single-Lane Approach Intersections

For single-lane approach intersections, there are regions for which either signal control or AWSC control provide minimal delays. There is also a region in which either of the three control types provides for level of service A or B delays.

Figures 57 and 58, a synthesis of the work presented earlier, are presented as guidelines only. They are to be used only as an aid as the transportation engineer considers a broad range of factors that affect the operation of the intersection. There are several traffic flow regions in which the procedures note that all three control types perform with a good level of service. In these cases, other factors need to be considered.

Figure 57 shows the flow regions for which each intersection control type will yield minimum subject approach delay. In region 1, all intersection control types would result in level of service A or B; that is, minor street or subject approach delays would be less than 10 to 15 seconds per vehicle. In region 2, signal control would result in the lowest approach delays. In region 3, both signal control and AWSC would yield about the same level of approach delay. In region 4, AWSC would yield minimum delays.

Figure 58 shows those flow regions for which each intersection control type will yield minimum intersection delay. In region 1, all intersection control types would result in level of service A or B; that is, average intersection delay would be less than 10 to 15 seconds per vehicle. In region 2, signal control would result in the lowest intersection delays. In region 3, both both signal control and TWSC would yield about the same level of approach delay.

6.2 Multi-Lane Approach Intersections

For multi-lane approach intersections, the complexity of traffic flow interactions argues, in most cases, for signal control. Even though the delay forecasts for AWSC intersections are lower for low flow rates, signal control will most likely yield optimal operations.

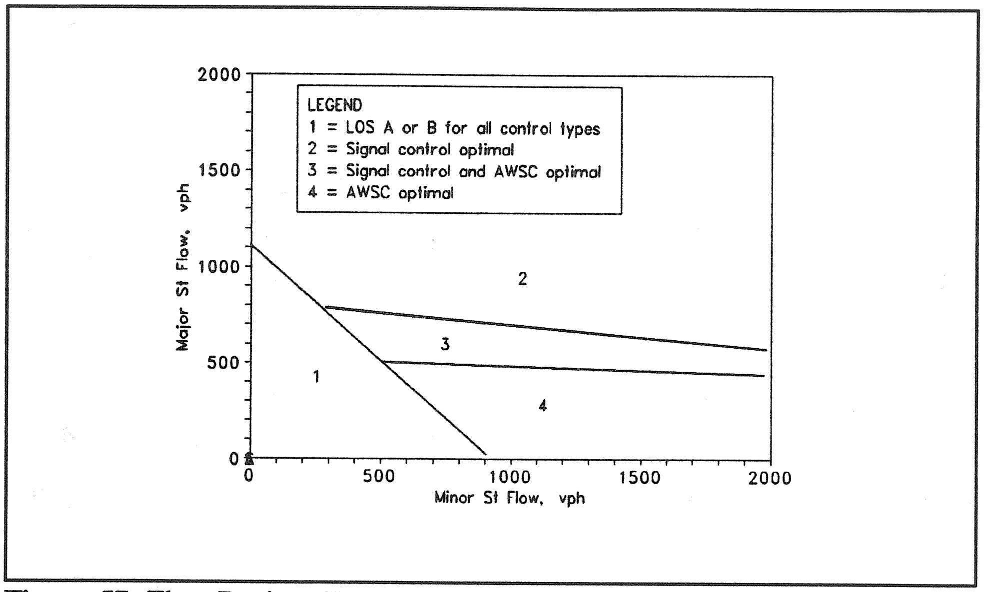

Figure 57. Flow Regions For Minimum Subject Approach Delay

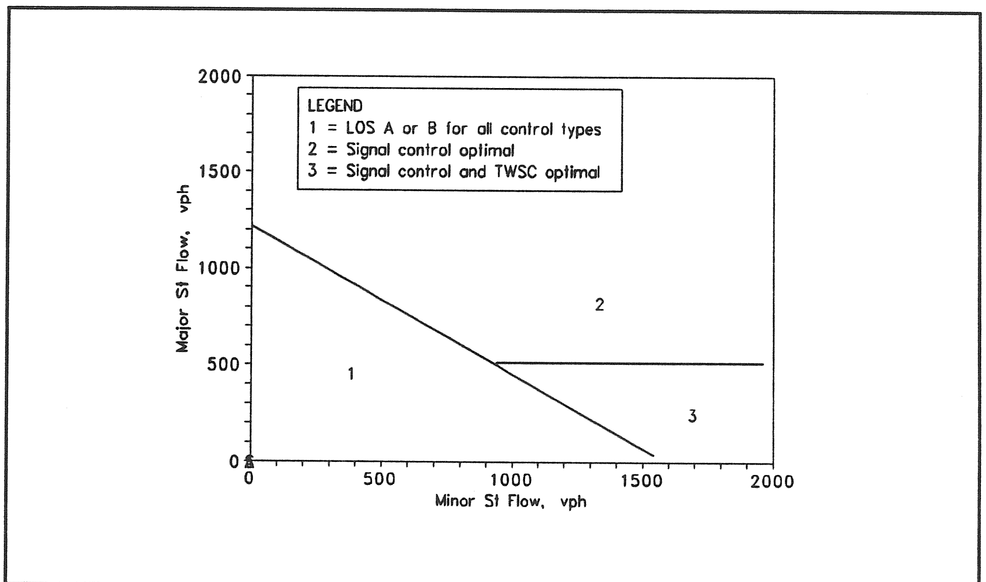

Figure 58. Flow Regions For Minimum Intersection Delay

7. SUMMARY AND CONCLUSIONS

The purpose of this report is to present the results of a study of the operational performance of single-lane and multi-lane approach intersections under a range of traffic flow conditions. Simulation models for signal control, AWSC and TWSC were used to produce delay estimates.

7.1 Single-Lane Approach Intersections

For low volumes, all three intersection control types result in level of service A or B operations, based on delay. When approach volumes exceed 300 vehicles per hour, signal control yields minimum subject approach and intersection delays. AWSC control yields minimum delay when major street flows are less than 500 vehicles per hour.

7.2 Multi-Lane Approach Intersections

The complexity of traffic flow interactions at multi-lane sites argues for signal control regardless of the traffic flow rates.

8. REFERENCES

1. U.S. Department of Transportation, Manual on Uniform Traffic Control Devices, Washington, D.C., 1989.

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APPENDIX

The results of the simulations for the single-lane approach intersections are given in the tables that follow.

Table 2. Subject Approach Delay Estimates, Major Street Volume = 200 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	100	100	6.3	2.1	4.2
200	200	100	100	2.5	3.1	6.0
300	300	100	100	2.8	4.7	8.5
400	400	100	100	3.1	7.0	12.1
500	500	100	100	2.5	10.5	17.2
600	600	100	100	2.6	15.7	24.4
700	700	100	100	2.4	23.4	34.6
800	800	100	100	2.6	34.9	49.1
900	900	100	100	2.8	52.1	69.7
1000	1000	100	100	3.2	77.8	98.9

Table 3. Subject Approach Delay Estimates, Major Street Volume = 400 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	200	200	10.9	2.7	7.5
200	200	200	200	6.7	4.3	10.7
300	300	200	200	3.3	6.5	15.1
400	400	200	200	3.7	9.8	21.5
500	500	200	200	4.2	14.7	30.5
600	600	200	200	5.0	22.0	43.3
700	700	200	200	4.1	32.9	61.4
800	800	200	200	4.9	49.3	87.2
900	900	200	200	4.7	73.7	123.7
1000	1000	200	200	5.2	110.1	

Table 4. Subject Approach Delay Estimates, Major Street Volume = 600 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	300	300	11.9	3.4	11.6
200	200	300	300	10.7	5.6	16.4
300	300	300	300	6.7	8.8	23.3
400	400	300	300	5.1	13.4	33.1
500	500	300	300	4.2	20.3	46.9
600	600	300	300	5.9	30.6	66.6
700	700	300	300	6.0	45.9	94.5
800	800	300	300	5.9	68.9	
900	900	300	300	7.3	103.3	
1000	1000	300	300	8.3		

Table 5. Subject Approach Delay Estimates, Major Street Volume = 800 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	400	400	19.3	4.1	14.1
200	200	400	400	12.7	7.3	20.0
300	300	400	400	9.9	11.7	28.3
400	400	400	400	7.8	18.1	40.2
500	500	400	400	6.8	27.7	57.1
600	600	400	400	7.0	42.0	81.0
700	700	400	400	7.3	63.5	114.9
800	800	400	400	9.8	95.6	
900	900	400	400	10.6		
1000	1000	400	400	15.0		

Table 6. Subject Approach Delay Estimates, Major Street Volume = 1000 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	500	500	20.7	4.8	17.1
200	200	500	500	10.7	9.2	24.3
300	300	500	500	13.7	15.2	34.5
400	400	500	500	10.4	24.1	48.9
500	500	500	500	9.4	37.3	69.4
600	600	500	500	10.1	57.1	98.5
700	700	500	500	11.1	86.9	
800	800	500	500	13.1	131.5	
900	900	500	500	17.6		
1000	1000	500	500	22.6		

Table 7. Subject Approach Delay Estimates, Major Street Volume = 1200 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	600	600	23.8	5.6	20.8
200	200	600	600	10.7	11.4	29.6
300	300	600	600	11.5	19.6	41.9
400	400	600	600	12.5	31.6	59.5
500	500	600	600	11.3	49.7	84.5
600	600	600	600	12.7	76.9	119.9
700	700	600	600	15.4	117.9	
800	800	600	600	21.2		
900	900	600	600	30.2		
1000	1000	600	600	44.0		

Table 8. Subject Approach Delay Estimates, Major Street Volume = 1400 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	700	700	30.1	6.3	25.3
200	200	700	700	18.3	13.9	36.0
300	300	700	700	16.2	24.8	51.0
400	400	700	700	15.9	41.1	72.4
500	500	700	700	15.1	65.6	102.8
600	600	700	700	17.8	102.6	
700	700	700	700	22.0		
800	800	700	700	30.7		
900	900	700	700	52.0		
1000	1000	700	700	111.7		

Table 9. Subject Approach Delay Estimates, Major Street Volume = 1600 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	800	800	33.1	7.1	30.8
200	200	800	800	24.6	16.7	43.7
300	300	800	800	16.2	31.1	62.1
400	400	800	800	15.9	52.7	88.1
500	500	800	800	19.7	85.7	125.0
600	600	800	800	22.0	135.7	
700	700	800	800	32.3		
800	800	800	800	54.8		
900	900	800	800	120.5		
1000	1000	800	800			

Table 10. Subject Approach Delay Estimates, Major Street Volume = 1800 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	900	900	41.9	7.8	37.5
200	200	900	900	24.6	19.8	53.2
300	300	900	900	22.9	38.4	75.5
400	400	900	900	24.6	67.0	107.2
500	500	900	900	27.1	110.8	
600	600	900	900	32.4		
700	700	900	900	56.9		
800	800	900	900	107.1		
900	900	900	900			
1000	1000	900	900			

Table 11. Subject Approach Delay Estimates, Major Street Volume = 2000 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	1000	1000	45.7	8.5	45.6
200	200	900	900	29.9	23.2	64.7
300	300	900	900	22.9	47.0	91.9
400	400	900	900	29.7	84.2	
500	500	900	900	43.1	142.1	
600	600	900	900	66.2		
700	700	900	900	117.9		
800	800	900	900			
900	900	900	900			
1000	1000	900	900			

Table 12. Intersection Delay Estimates, Major Street Volume = 200 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	100	100	6.0	2.1	2.1
200	200	100	100	5.7	3.0	4.0
300	300	100	100	5.1	4.4	6.4
400	400	100	100	4.9	6.4	9.7
500	500	100	100	5.5	9.5	14.3
600	600	100	100	5.6	14.2	20.9
700	700	100	100	5.8	21.3	30.3
800	800	100	100	6.0	31.8	43.6
900	900	100	100	6.7	47.7	62.7
1000	1000	100	100	7.1	71.5	89.9

Table 13. Intersection Delay Estimates, Major Street Volume = 400 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	200	200	5.6	3.0	2.5
200	200	200	200	6.0	4.3	5.3
300	300	200	200	6.3	6.1	9.1
400	400	200	200	6.1	8.9	14.3
500	500	200	200	6.1	13.1	21.8
600	600	200	200	6.4	19.4	32.5
700	700	200	200	7.3	28.7	47.8
800	800	200	200	7.6	42.8	69.7
900	900	200	200	9.1	63.9	101.2
1000	1000	200	200	10.6	95.6	

Table 14. Intersection Delay Estimates, Major Street Volume = 600 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	300	300	5.1	4.4	2.9
200	200	300	300	6.3	6.1	6.6
300	300	300	300	6.7	8.8	11.6
400	400	300	300	7.1	12.6	18.9
500	500	300	300	7.8	18.4	29.3
600	600	300	300	7.7	26.9	44.4
700	700	300	300	8.3	39.6	66.1
800	800	300	300	9.8	58.6	97.5
900	900	300	300	11.2	87.0	
1000	1000	300	300	14.1	129.8	

Table 15. Intersection Delay Estimates, Major Street Volume = 800 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	400	400	4.9	6.4	2.8
200	200	400	400	6.1	8.9	6.7
300	300	400	400	7.1	12.6	12.1
400	400	400	400	7.8	18.1	20.1
500	500	400	400	8.4	26.1	31.7
600	600	400	400	5.1	37.9	48.6
700	700	400	400	6.4	55.3	73.1
800	800	400	400	7.9	81.3	108.7
900	900	400	400	10.8	120.1	
1000	1000	400	400	15.0		

Table 16. Intersection Delay Estimates, Major Street Volume = 1000 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	500	500	5.5	9.5	2.9
200	200	500	500	6.1	13.1	6.9
300	300	500	500	7.8	18.4	12.9
400	400	500	500	8.4	26.1	21.7
500	500	500	500	9.4	37.3	34.7
600	600	500	500	10.6	53.8	53.7
700	700	500	500	12.8	78.0	81.6
800	800	500	500	11.3	113.9	122.1
900	900	500	500	21.0		
1000	1000	500	500	29.4		

Table 17. Intersection Delay Estimates, Major Street Volume = 1200 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	600	600	5.6	14.2	3.0
200	200	600	600	6.4	19.4	7.4
300	300	600	600	7.7	26.9	14.0
400	400	600	600	5.1	37.9	23.8
500	500	600	600	10.6	53.8	38.4
600	600	600	600	8.5	76.9	59.9
700	700	600	600	11.9	110.8	91.6
800	800	600	600	21.6		
900	900	600	600	25.9		
1000	1000	600	600	46.5		

Table 18. Intersection Delay Estimates, Major Street Volume = 1400 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	700	700	5.8	21.3	3.2
200	200	700	700	7.3	28.7	8.0
300	300	700	700	8.3	39.6	15.3
400	400	700	700	6.4	55.3	26.3
500	500	700	700	12.8	78.0	42.8
600	600	700	700	11.9	110.8	67.3
700	700	700	700	17.1		103.5
800	800	700	700	26.2		
900	900	700	700	48.2		
1000	1000	700	700	107.9		

Table 19. Intersection Delay Estimates, Major Street Volume = 1600 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	800	800	6.0	31.8	3.4
200	200	800	800	7.6	42.8	8.7
300	300	800	800	9.8	58.6	16.9
400	400	800	800	7.9	81.3	29.4
500	500	800	800	11.3	113.9	48.1
600	600	800	800	21.6		76.0
700	700	800	800	26.2		117.5
800	800	800	800	48.8		
900	900	800	800	108.3		
1000	1000	800	800			

Table 20. Intersection Delay Estimates, Major Street Volume = 1800 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	900	900	6.7	47.7	3.8
200	200	900	900	9.1	63.9	9.7
300	300	900	900	11.2	87.0	18.9
400	400	900	900	10.8	120.1	33.0
500	500	900	900	21.0		54.3
600	600	900	900	25.9		86.3
700	700	900	900	48.2		134.0
800	800	900	900	108.3		
900	900	900	900			
1000	1000	900	900			

Table 21. Intersection Delay Estimates, Major Street Volume = 2000 vph

SUB-VOL	OPP-VOL	CONL-VOL	CONR-VOL	SIGNAL	AWSC	TWSC
100	100	1000	1000	7.1	71.5	4.1
200	200	1000	1000	10.6	95.6	10.8
300	300	1000	1000	14.1		21.2
400	400	1000	1000	15.0		37.2
500	500	1000	1000	29.4		61.7
600	600	1000	1000	46.5		98.4
700	700	1000	1000	107.9		
800	800	1000	1000			
900	900	1000	1000			
1000	1000	1000	1000			